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TESIS DOCTORAL

RAZONAMIENTO QUÍMICO EN EL AULA

Caracterización del razonamiento químico que subyace a las explicaciones individuales y colectivas construidas por estudiantes de enseñanza media en el tópico de disoluciones

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Tabla de contenido

Índice de tablas y figuras

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1 Resumen

El siguiente compendio de artículos reúne los resultados obtenidos del desarrollo de esta tesis doctoral, centrada en la visibilización del razonamiento que subyace a las explicaciones elaboradas por los estudiantes en el aula de química. El propósito de esta investigación fue contribuir con evidencia empírica a la caracterización del razonamiento individual y colectivo elicitado durante el proceso de aprendizaje de la química en etapa escolar. La investigación se realizó en el contexto educacional chileno, en un establecimiento de la Región Metropolitana de dependencia particular subvencionada, cuyos participantes cursaban segundo año de enseñanza media. Los datos fueron recopilados mediante grabaciones de audio y video para acceder a las interacciones de aula, además de recolectar las producciones escritas de los 78 estudiantes participantes del estudio. El estudio se llevó a cabo mediante una propuesta posicionada desde un enfoque sociocultural del aprendizaje, integrando visiones de razonamiento desde la psicología educativa, filosofía de la ciencia y educación química (Grotzer, 2003; Russ, Scherr, Hammer, & Mikeska, 2008; Sevian & Talanquer, 2014). El análisis cualitativo de los 75 estudios de caso permitió visibilizar, mediante la construcción de diagramas, el razonamiento subyacente a las explicaciones escritas por los estudiantes. Del mismo modo, el análisis a las interacciones de aula abrió paso a caracterizar la manera en que las intervenciones docentes modelan el razonamiento colectivo en el aula de química. Se espera que los resultados de esta tesis doctoral contribuyan al trabajo de investigadores y docentes interesados en promover formas complejas de razonamiento en el aprendizaje de la química escolar.

2 Introducción

Los artículos presentados en este compendio son resultado del trabajo en torno al proyecto de tesis doctoral presentado en diciembre de 2016, y cuyo desarrollo es conducente al grado de Doctor en Ciencias de la Educación. El proyecto de tesis presentado en 2016 tenía como propósito abordar la enseñanza y aprendizaje de la química con énfasis en el rol del docente en el proceso de movilización del razonamiento de sus estudiantes en el aula de química. La tesis proponía abordar el conocimiento pedagógico del contenido del profesor de química (Shulman, 1987; Talanquer, 2004) en una de sus cinco dimensiones: el conocimiento sobre las necesidades y dificultades del estudiantado (Magnusson, Krajcik, & Borko, 1999).

Durante la presentación de la candidatura doctoral la comisión entregó su retroalimentación al proyecto de tesis. Los integrantes de esta comisión consideraron que abordar el rol del docente en base a su conocimiento pedagógico del contenido en la movilización de los razonamientos escolares en química, es un área relevante a nivel internacional y un campo emergente en nuestro país, evidenciando la relevancia de abordar esta temática en el contexto chileno. Sin embargo, debido a la especificidad que requiere el análisis del razonamiento del estudiantado se realizaron las siguientes sugerencias para delimitar el objeto de estudio:

- Definir el foco de estudio en enseñanza o aprendizaje.
- Abordar el estudio del razonamiento mediante una práctica científica que permita evidenciar estos procesos en el aula.
- Situar el estudio en un tópico específico de la química.

En los meses posteriores a la defensa de candidatura se trabajó en la incorporación de estas sugerencias en el proyecto, lo que llevó a tomar decisiones que permitieran focalizar el objeto de estudio y concretar los procesos mediante los cuales podríamos acceder al mismo. De esta manera, la incorporación de las recomendaciones de la comisión se puntualizó en los siguientes hechos.

La tesis doctoral se centra en el aprendizaje de la química desde una perspectiva sociocultural (John-Steiner & Mahn, 1996). En esta perspectiva, las oportunidades de interacción entre los integrantes del proceso de aprendizaje cobran vital importancia, pues es durante estas interacciones donde se genera la construcción de conocimiento (Mercer & Howe, 2012), y en este caso en específico el conocimiento científico escolar.

La decisión sobre la práctica científica que permita acceder al razonamiento de los estudiantes, se llevó a cabo en función de criterios curriculares y requerimientos de una tarea que apunte a formas de razonamiento complejo de acuerdo con trabajos internacionales en el área (Grotzer, 2012; Izquierdo & Aliberas, 2004; Talanquer, 2010). De esta forma, considerando las prácticas científicas presentes en el currículum chileno y las investigaciones en torno a las formas de razonamiento de estudiantes de diversos niveles en el marco internacional, la práctica científica seleccionada es la construcción de explicaciones. Esta práctica se destaca por su relevancia en el aprendizaje de las ciencias pues involucra el establecimiento de relaciones causales que den sentido al fenómeno en estudio (Izquierdo & Aliberas, 2004) y que permitirán visualizar el razonamiento del estudiantado.

Finalmente, el tópico específico en el cual se contextualiza el estudio fue seleccionado en función de dos criterios principales: (a) marco curricular de la asignatura de química en Chile y (b) temporalidad escolar en el cual se produjo el acercamiento a los participantes del estudio. Así el tópico específico seleccionado es disoluciones, específicamente en propiedades coligativas en el descenso del punto de congelación, en el nivel de segundo año de enseñanza media. En esta temática la literatura reporta posibles formas de razonamiento de estudiantes universitarios en torno a este tópico al elaborar explicaciones (Talanquer, 2010) y algunas ideas iniciales sobre los factores que inciden en el entendimiento del proceso (Çokadar, 2009).

De esta manera el estudio del razonamiento de los estudiantes se enfocó en un tópico y en una práctica científica específica, que permitiera visibilizar sus formas de razonar, y de qué manera este razonamiento se manifiesta y moviliza durante la clase de química. La concreción de las decisiones anteriormente descritas delimitó el foco de estudio, el que finalmente tiene como objetivo *"caracterizar el razonamiento individual y colectivo que subyace a la construcción de explicaciones en el aprendizaje de la química escolar".*

En el presente compendio se da a conocer la propuesta desarrollada en torno a la visibilización del razonamiento de estudiantes en etapa escolar dividida en dos etapas. Los resultados de cada una de estas etapas son detallados en los artículos de investigación que forman este compendio. Con el objetivo de contextualizar el estudio realizado, en el siguiente apartado se presenta la problemática y aspectos teóricos relevantes bajo los cual se sustenta esta investigación.

2.1 Planteamiento del problema

El desarrollo de un pensamiento crítico frente a problemáticas sociales, ambientales y tecnológicas a las que nos enfrentamos en la actualidad es una de las principales preocupaciones de los marcos de enseñanza de las ciencias a nivel mundial (National Research Council, 2013). Posicionarnos en una sociedad como personas informadas y críticas ha despertado la necesidad de formar futuras generaciones capaces de razonar sobre las consecuencias que sus decisiones pueden generar en el entorno (Bybee, McCrae, & Laurie, 2009).

Estos lineamientos internacionales son compartidos en Chile, cuyo currículum escolar considera estos principios como orientadores para la educación científica (Ministerio de Educación, 2015). No obstante, se han evidenciado bajos niveles de desempeño tanto en mediciones estandarizadas internacionales (PISA) como nacionales (SIMCE). En la evaluación de competencias científicas realizadas por el programa PISA el año 2015, los estudiantes chilenos, a pesar de obtener los mejores resultados en el ámbito latinoamericano (447 puntos), presentan niveles alejados del puntaje promedio de la OCDE (493). En relación con la dimensión referida a las explicaciones científicas, los resultados muestran que el 31% de los estudiantes chilenos están situados en el nivel básico en la explicación de fenómenos científicos (Agencia de Calidad de la Educación, 2017). En definitiva, los resultados muestran que los estudiantes chilenos están poco preparados para explicar fenómenos y utilizar evidencias científicas para interpretar y resolver problemas de la vida cotidiana que involucran la ciencia y la tecnología (Gutiérrez, 2008)

Promover la construcción de explicaciones escolares situadas en cuestiones socio científicas cercanas a los estudiantes, se presenta como una oportunidad para desarrollar complejas formas de razonamiento (Grotzer, 2012). No obstante, construir una explicación no es una labor fácil pues requiere que estas complejas conexiones sean adecuadas para dar respuesta a la tarea (Russ et al., 2008) y coherentes con el modelo o teoría científica que permite comprender el fenómeno estudiado (Izquierdo & Aliberas, 2004).

Considerando que las explicaciones expresadas por los estudiantes son producto de su razonamiento frente a una tarea en un contexto específico (Talanquer, 2010a; Weinrich & Talanquer, 2016), el análisis de estas producciones ha permitido a investigadores acceder a las formas de razonamiento del estudiantado (Disessa, 2014; Machamer, Darden, & Craver, 2000; Russ, Coffey, Hammer, & Hutchison, 2009; Russ, Scherr, Hammer, & Mikeska, 2008), presentando evidencia de que su caracterización permite explorar y comprender los orígenes de numerosas dificultades presentes en el aprendizaje de las ciencias (Talanquer, 2005; Viennot, 2001).

Estudios desde la psicología y filosofía de la ciencia han generado importante evidencia sobre algunas de las características del razonamiento del estudiantado. Parte de estos estudios ha permitido operacionalizar los componentes de razonamientos causales complejos (Machamer et al., 2000; Russ et al., 2008), otros proponen tipologías sobre la causalidad (Grotzer, 2012; Grotzer, 2003) y al mismo tiempo revelan desafíos sobre cómo abordar la enseñanza en torno a los razonamientos que se movilizan en el aula de ciencias, específicamente en química (Sevian & Talanquer, 2014; Talanquer, 2018b). En el contexto chileno no hemos encontrado investigación asociada a las formas de razonamiento que subyacen a las explicaciones que los estudiantes construyen en el aula de química, siendo necesario aportar con investigaciones que entreguen evidencia al respecto.

Esta tesis doctoral, pretende caracterizar las formas de razonamiento expresadas por estudiantes en la clase de química en etapa escolar y la movilización de estos razonamientos cuando se enfrentan a la tarea de construir colectivamente explicaciones de fenómenos cotidianos que involucran el conocimiento químico en el aula. El propósito de esta investigación es contribuir con un análisis sistemático de las evidencias de desempeño de estudiantes frente a la tarea de explicar, que nos permitan comprender de qué manera estas formas de razonamiento se van transformando durante los procesos de enseñanza y aprendizaje. La evidencia recolectada y el análisis de la misma contribuirá además a la generación de criterios que orienten la práctica pedagógica.

El desarrollo de esta tesis se sustenta en un marco teórico que en una primera etapa vincula investigaciones sobre razonamiento causal desde el campo de la psicología educacional, filosofía de la ciencia y educación química. Estos marcos han sido los elementos estructurantes para la construcción de la propuesta de análisis para cada una de las producciones de los estudiantes en la primera fase del estudio. En un segundo momento, el marco teórico y de análisis propuesto se complementa vinculando a éste una visión de aprendizaje desde la perspectiva sociocultural, poniendo especial énfasis en la construcción de razonamientos colectivos en base a las interacciones de aula modeladas por las intenciones docentes.

2.2 Razonamiento causal y construcción de explicaciones en el aprendizaje de la química

Desarrollar explicaciones en el aula de ciencias implica establecer relaciones causales que nos lleven a entender el por qué y cómo se producen ciertos cambios en un sistema (Izquierdo & Aliberas, 2004). Este proceso implica que las formas de razonamiento que los estudiantes construyen en su vida cotidiana se aproximen progresivamente al razonamiento de la disciplina (Sevian, Ngai, Szteinberg, Brenes, & Arce, 2015). Se esperaría entonces que los estudiantes, partiendo de su razonamiento intuitivo, desarrollen estrategias de pensamiento que permitan dar respuestas apropiadas a problemas escolares y cotidianos. Sin embargo, estudios a nivel universitario en el aprendizaje de la química, dan cuenta de la persistencia en el estudiantado del uso de heurísticos o atajos en el razonamiento que dificultan el proceso de construcción de explicaciones científicas (Maeyer & Talanquer, 2010), factor que hace relevante el diseño de estrategias de enseñanza adecuadas para alcanzar formas de razonamiento coherentes a la tarea.

Trabajos en torno al razonamiento que subyace a las explicaciones en ciencias han contribuido con importantes hallazgos en este campo. Estudios han caracterizado niveles de sofisticación del razonamiento expresado en el aprendizaje de la química a nivel universitario (Sevian & Talanquer, 2014). Otros han visibilizado la complejidad de la construcción relaciones causales (Grotzer, 2012) Así como también se ha reportado la dependencia del desempeño de los estudiantes frente a la tarea de explicar en función del tipo de pregunta que antecede la tarea (Gilbert, Boulter, & Rutherford, 2000; Yeo & Gilbert, 2014) y factores contextuales como el tiempo asignado a la misma (Weinrich & Talanquer, 2015).

En el contexto chileno, existen trabajos enfocados en cómo profesores en formación construyen explicaciones en ciencias en un contexto de evaluación de pares (Cabello y Topping, 2014). Este estudio evidenció cambios en las concepciones de los profesores acerca de la calidad de las explicaciones y en su habilidad para explicar conceptos científicos, dando cuenta de que el trabajo intencionado en torno a esta habilidad mejora el desempeño de los docentes teniendo un impacto en su conocimiento pedagógico del contenido. En el contexto escolar, se han estudiado las explicaciones de estudiantes en el tópico de electroquímica (Camacho, 2012), encontrando que las actividades de experimentación y aplicación son claves para el desarrollo de esta habilidad cognitivo lingüística. Desde el campo de los planos de análisis y desarrollo (Labarrere y Quintanilla, 2002), se ha identificado la manera en que los estudiantes podrían transitar entre estas dimensiones en el contexto de la resolución de problemas en el aula de ciencias. Sin embargo, no hemos encontrado literatura asociada a visibilizar el razonamiento que subyace a las producciones de los estudiantes.

La caracterización del razonamiento que subyace la construcción de explicaciones ha nivel internacional ha tenido lugar desde dos corrientes principales: la psicología (Grotzer, 2012; Grotzer & Shane Tutwiler, 2014; Perkins & Grotzer, 2005) y filosofía de la ciencia (Machamer et al., 2000; Russ et al., 2008). Aportes desde ambos campos han permitido distinguir entre diversas formas de causalidad (Grotzer, 2012), así como la identificación de formas de razonamiento que transitan desde niveles descriptivos hacia razonamientos canónicos o denominados mecanístico (Machamer et al., 2000; Russ et al., 2008).

En la investigación sobre el razonamiento mecanístico la literatura reporta dificultades en la distinción de este tipo de razonamiento frente a otros como el causal simple. Russ y colaboradores (2008) desde la visión de la filosofía de la ciencia abordaron esta problemática elaborando un conjunto de criterios que permiten distinguir la presencia de ambos tipos de razonamiento (Russ et al., 2008). Este marco involucra 7 categorías que se describen en la Tabla 2.1. Los autores de este trabajo señalan que una de las características principales que da cuenta de un razonamiento mecanístico es la presencia de detalles sobre la organización de las entidades (componentes del sistema en estudio) que producen un cambio en el objeto de estudio. Esta característica, no es compartida en las explicaciones netamente causales pues éstas sólo buscan dar cuenta del porqué se lleva a cabo un determinado comportamiento o fenómeno sin profundizar en el mecanismo o proceso que lo desencadena, ni en la organización espaciotemporal de las entidades involucradas.

Tabla 2.1. Esquema de cogidos elaborado por Russ y colaboradores (2008) para la caracterización del razonamiento mecanístico a partir del análisis del discurso de estudiantes

Código	Descripción
Descripción del objeto de estudio	Descripción del fenómeno. Los científicos pueden comenzar conociendo el fenómeno para luego investigar el mecanismo que lo produce, o pueden describir los fenómenos como predicciones basadas en su conocimiento previo de los componentes relevantes. Cuando los estudiantes declaran o demuestran claramente el fenómeno o resultado particular que intentan explicar, codificamos sus comentarios como "describiendo el fenómeno objetivo".
Identificación de las condiciones	Las condiciones particulares del entorno que permiten que el mecanismo funcione. Por ejemplo, el estudiante podría decir "Sostuve ambas latas de bebida debajo del agua antes de liberarlas".
Entidades	Los científicos reconocen que un componente de las descripciones mecanicistas son las entidades: las cosas que juegan un papel en la producción del fenómeno. Cuando los estudiantes reconocen objetos que afectan el resultado del fenómeno, codificamos dichos comentarios como "entidades de identificación" incluso si la entidad ha sido identificada previamente.
Propiedades de entidades	Identificar y aislar esas propiedades de las entidades relevantes para el resultado es una parte vital del descubrimiento científico. Al codificar para "identificar propiedades de entidades", buscamos estudiantes que se involucren en esta práctica científica al articular propiedades generales de entidades que son necesarias para que este mecanismo en particular funcione. Por ejemplo, un estudiante puede decir: "Las moléculas de agua son pequeñas bolas duras que rebotan en todo".
Actividades	Junto con la identificación de las entidades en un mecanismo, los científicos también identifican las actividades relevantes: "las diversas actividades en las que participan estas entidades" (Craver y Darden, 2001). Los estudiantes que articulan las acciones e interacciones que ocurren entre entidades se codifican como "identificación de actividades". Usamos este código cada vez que los estudiantes describen las cosas que hacen las entidades que causan cambios en las entidades circundantes, incluso si la actividad ha sido identificada previamente. Por ejemplo, un estudiante podría decir: "Cada molécula de agua individual empuja hacia arriba las moléculas en la parte superior".
Organización	En la mayoría de los casos, el mecanismo depende de cómo están organizadas espacialmente las entidades, dónde están ubicadas y cómo están estructuradas. Cuando los estudiantes prestan atención a esas características, codificamos sus comentarios como " identificación de organización de entidades". Por ejemplo, un estudiante puede decir: "El agua debajo del aceite lo empuja, mientras que el alcohol sobre el aceite también lo empuja". Este código no aparece en los datos que se presentan a continuación, pero ha sido crucial en el análisis de las discusiones de otros estudiantes (Russ & Hutchison, 2006).
Cadena de eventos	Observamos a los estudiantes razonar sobre una etapa en un mecanismo basado en lo que se conoce de otras etapas de ese mecanismo particular y codificamos este tipo de razonamiento como "cadena de eventos". Cuando los estudiantes encadenan eventos hacia atrás, responden a las preguntas como: ¿Qué actividades podrían haber dado lugar a entidades con estas propiedades? o ¿Qué entidades eran necesarias para que esta actividad haya ocurrido? Cuando los estudiantes van encadenando en forma de predicción, responden a las preguntas: ¿En qué actividades se espera que participen estas entidades con estas propiedades? o Si ocurriera esta actividad, ¿qué cambios esperaría en las entidades cercanas? ¿Y sus propiedades?

En los últimos años investigaciones se han enfocado en develar cómo los estudiantes pueden desarrollar formas de razonamiento mecanístico en ciencias, logrando un gran desarrollo en el campo de la biología (Southard, Espindola, Zaepfel, & Bolger, 2017; van Mil, Postma, Boerwinkel, Klaassen, & Waarlo, 2016). El interés en este campo ha ido en incremento y actualmente es posible encontrar investigaciones que analicen el razonamiento mecanístico en el aprendizaje de la química (Becker et al., 2016; Bhattacharyya, 2013; Talanquer, 2018a) ampliando las referencias en torno a cómo los estudiantes llegan a conclusiones o explicaciones que no son del todo aceptadas por la comunidad científica, las que actualmente se conocen como ideas alternativas. Esto además se ve reforzado por los hallazgos que apuntan a que la construcción de explicaciones en base al razonamiento mecanístico no asegura una correcta relación causal de los componentes elicitados, pues es posible que se utilicen mecanismos que no son coherentes con el modelo científico asociado al fenómeno que se pretende explicar (Russ et al., 2008). O bien que estas ideas solo se enmarquen en un tipo de explicación estática limitando el entendimiento y aplicación de procesos dinámicos en el aprendizaje de la química (Talanquer,2010).

En la investigación sobre educación química, específicamente en el aprendizaje de esta disciplina a nivel universitario, Sevian y Talanquer (2014) desarrollaron una progresión del razonamiento de estudiantes que describe cómo sus explicaciones pueden localizarse en cuatro niveles: descriptivo, relacional, de causalidad lineal o multicomponencial. El último nivel de esta progresión puede ser asociado a uno del tipo mecanístico. La descripción de cada una de estas categorías involucra la incorporación progresiva de variables que permiten explicar el comportamiento de un sistema en estudio, considerando cómo las explicaciones se movilizan desde causalidades estáticas a dinámicas, desde narraciones que presentan factores de manera aislada hasta aquellas que consideran las explicaciones como cadenas de eventos. Detalles de estas categorías de sofisticación del razonamiento químico son presentadas en la Tabla 2.2.

Tabla 2.2. Niveles de sofisticación del razonamiento químico propuestos por Sevian y Talanquer (2014)

Modo de Razonamiento	Descriptor
Descriptivo	Los fenómenos descritos reafirman que las cosas son como son, sin referirse a las causas. Se centran principalmente en las características más destacadas y explícitas de un sistema. Fuerte influencia de similitud superficial
Relacional	Se establecen correlaciones entre las propiedades y comportamientos, pero no se explican o justifican. Se evidencian características explícitas e implícitas de un sistema. - Uni-relacional: explicación basada en una única relación. - Multi-relacional: explicación basada en múltiples relaciones.
Lineal causal	Aunque la influencia de muchos factores puede ser reconocida, los fenómenos tienden a reducirse con el resultado de la acción de un único agente en otras entidades; mecanismos propuestos implican relaciones causa-efecto y lineales de cadenas secuenciales de eventos. Se evidencian características explícitas e implícitas de un sistema. - Cadena lineal: cadenas causales simples se utilizan en las explicaciones. - Multi-relacional: una combinación de cadenas causales simples y correlaciones injustificadas se utilizan en las explicaciones.
Multicomponencial	Los fenómenos son considerados como el resultado de la interacción estática o dinámica de más de un factor y las interacciones directas de varios componentes. Se construyen historias causales. Se evidencian características explícitas e implícitas de un sistema. - Aislado: efectos de varias variables se consideran y se pesan por separado. - Integrado: explicaciones como historias interconectadas de cómo las diferentes variables afectan a las entidades involucradas.

Estudios realizados en el campo de la química revelan la complejidad en la construcción de explicaciones en esta disciplina, debido a que las relaciones causales que explican el fenómeno en estudio involucran entidades abstractas cuyas propiedades e interacciones son la causa de los efectos observados, siendo una de las dificultades intrínsecas de esta ciencia (Caamaño, 2000). En este escenario, comprender fenómenos desde el aprendizaje de la química se transforma en un desafío para nuestros estudiantes quienes consideran esta ciencia como un saber incomprensible, distante (Izquierdo, 2004) y poco motivador (Vázquez & Manassero, 2008).

Las contribuciones al estudio del razonamiento desde diversos campos de investigación y las dificultades intrínsecas, instruccionales y del estudiantado en el campo de la química (Caamaño & Oñorbe, 2004), dan cuenta de la importancia de guiar la construcción de modelos causales para el desarrollo del conocimiento científico a nivel escolar (Grotzer, 2003). El acompañamiento en el desarrollo de la habilidad de explicar en ciencias a nivel escolar es crucial, pues se conoce que el solo hecho de activar un razonamiento complejo no se encuentra inmediatamente alineado a las teorías científicas que soportan los hechos que se pretenden explicar (Russ et al., 2008).

Grotzer (2003, 2012) reconociendo la necesidad de generar instancias de andamiaje en la construcción de relaciones causales, propone una tipología causal presente en la Figura 2.3 La autora en base al trabajo desarrollado sobre razonamiento causal sugiere directrices de enseñanza para su abordaje en el aula, como estrategias de cómo explicitar las causalidades complejas aplicadas a contextos cotidianos. En sus estudios se presenta la causalidad como un elemento importante en la comprensión de sucesos en nuestra vida diaria (Grotzer, 2003; Grotzer & Perkins, 2000; Grotzer & Tutwiler, 2014), enfatizando en cómo la construcción colectiva del entendimiento de la causalidad a nivel escolar contribuye a la formación de futuras generaciones de ciudadanos críticos y conscientes de las repercusiones de sus acciones en el entorno.

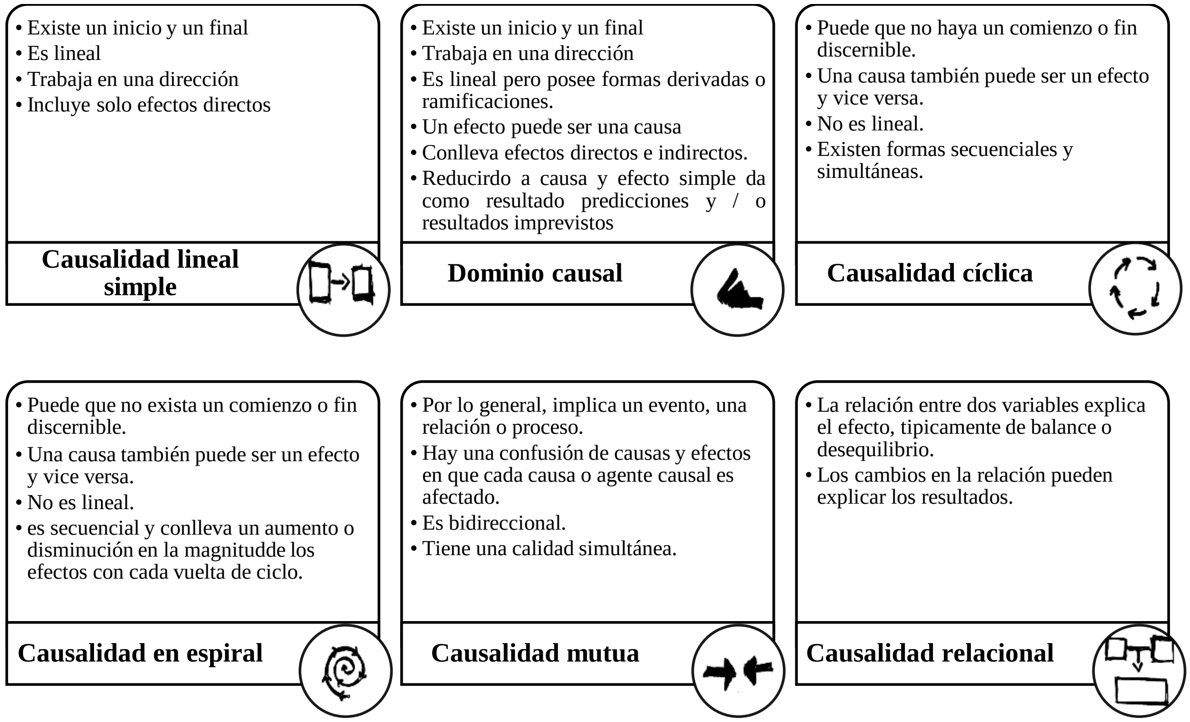

Figura 2.3. Seis patrones causales propuestos por Grotzer (2012).

Si bien los aportes de investigaciones como Russ y colaboradores (2008) operacionalizando los componentes del razonamiento mecanístico, las formas de causalidad presentadas por Grotzer (2012) y los niveles de razonamiento químico abordados por Sevian y Talanquer (2014), han contribuido a robustecer el conocimiento sobre las formas de razonamiento que construyen los estudiantes en el aprendizaje de la química, aún se presentan desafíos sobre cómo visibilizar las formas de razonamiento que se movilizan en las interacciones de aula y cómo estas progresivamente convergen hacia producciones cercanas a las teorías científicas que permiten comprender los fenómenos a nivel escolar.

2.3 La enseñanza y aprendizaje desde un enfoque sociocultural en la construcción de razonamiento colectivo en el aula

El desarrollo de esta tesis doctoral se sitúa en una perspectiva sociocultural de enseñanza y aprendizaje. Como tal, consideramos que el desarrollo cognitivo es resultado de las interacciones sociales (John-Steiner & Mahn, 1996; Vygotsky, 1978). Esas interacciones se desarrollan a través de eventos comunicativos, modelados por nuestra naturaleza social (Mercer, 2004), donde el lenguaje es un elemento esencial en la comunicación entre las dimensiones intramental (individual) e intermental (colectiva) (Mercer, 2010, 2013b).

En esta perspectiva, estudios evidencian que la construcción de razonamientos complejos estaría fuertemente relacionada con las posibilidades de interacción que se desarrollan durante el proceso de aprendizaje. Estas interacciones involucran el lenguaje hablado o escrito, las que se plantean como una herramienta para el desarrollo del razonamiento colectivo (Mercer, 2004). Entregar oportunidades a los estudiantes de construir explicaciones individualmente, activa la dimensión intramental, que luego bajo la perspectiva sociocultural demanda compartir las ideas que se desprenden de esta dimensión con el propósito de analizar diferentes puntos de vista (Mercer, 2013). En el contexto escolar estas oportunidades de intercambio de ideas se llevan a cabo en los procesos de interacción de aula, que permiten a los estudiantes expresar y reorganizar sus ideas, corroborando o reformulando sus respuestas iniciales. Siendo estas instancias, las que promueven la construcción de razonamientos colectivos, que luego de procesos iterativos favorecen la comprensión mutua en la interacción social promoviendo la convergencia del conocimiento (Jeong & Chi, 2007).

Para que lo anterior ocurra se esperaría que un fructífero desarrollo de las interacciones generadas durante la tarea de comprender y explicar un determinado fenómeno en el aula, conduzca a los estudiantes a converger en formas de razonamiento coherentes con los modelos o teorías científicas que dan respuesta a los hechos observados. Para ello el rol de los docentes es esencial; ellos orquestan esta conversación en el aula haciendo que los estudiantes aprendan ciencia a través del uso estratégico de determinados movimientos de habla (Michaels & O'connor, 2012; Windschitl, Thompson, & Braaten, 2018).

Estudios relacionados con la labor docente en el contexto de un enfoque constructivista de enseñanza y aprendizaje, se pueden clasificar en dos niveles de investigación. El primero de ellos enfocado en el conocimiento que caracteriza la labor docente o también conocido como conocimiento pedagógico del contenido (Alvarado, Cañada, Garritz, & Mellado, 2015; Garriz, Nieto, Padilla, Reyes-cárdenas, & Velasco, 2008; Magnusson, Krajcik, & Borko, 1999; Shulman, 1987). Y en un segundo grupo se encuentran aquellos que analizan y describen las prácticas claves que desarrolla un docente al construir el discurso en el aula (Aydeniz & Dogan, 2016; Bell & Cowie, 2001; Grossman et al., 2009; McDonald et al., 2014; Thompson, Windschitl, & Braaten, 2013; Windschitl, Thompson, Braaten, & Stroupe, 2012). A continuación, se entrega una breve descripción de ambos focos de estudio.

El conocimiento pedagógico del contenido (Shulman, 1987), es reconocido por más de 30 años como uno de los saberes que forma parte del conocimiento profesional docente, el que se encuentra en constante evolución y expansión (Parga y Mora, 2014). A lo largo de los años se han considerado diversas definiciones sobre conocimiento pedagógico del contenido (CPC), pero actualmente en su mayoría se ha consensuado regresar a su definición inicial que considera al CPC como uno de los saberes base del profesor, representando la conexión entre el contenido y la pedagogía, reflejando el entendimiento de cómo un tópico particular es organizado, representado y adaptado para su enseñanza en función de las características de los estudiantes (Shulman, 1987).

El CPC es un conocimiento dinámico, presente de forma tácita en todos los docentes, desarrollado de manera intuitiva durante su ejercicio en base a la experiencia, creencias y concepciones de la enseñanza que posee un profesor (Alvarado, Canada, Garritz y Mellado, 2015). Este conocimiento puede ser desarrollado de forma robusta y explícita por parte de los profesores, en base a evidencia científica en el campo y ser compartido y aplicado por muchos docentes, lo que se conoce en la literatura como conocimiento pedagógico del contenido canónico (Garritz, 2015).

Entre las investigaciones enfocadas en descifrar cuántos y cuáles serían las sub-dimensiones de este conocimiento, Magnusson y col. (1999) se plantean como el modelo predominante entre las investigaciones en profesores de ciencias (Abell, 2008). Este modelo reconoce al conocimiento pedagógico del contenido como un nuevo tipo de conocimiento conformado por 5 sub-dimensiones: (1) el conocimiento de las ideas previas y de los obstáculos de aprendizaje de sus estudiantes, (2) el marco curricular, (3) estrategias de enseñanza, (4) evaluación y (5) la orientaciones hacia la enseñanza de las ciencias (Magnusson y col., 1999).

En el contexto de los docentes de química, el conocimiento pedagógico del contenido de un buen profesor determina la elección de qué conceptos son importantes de enseñar, qué tipo de preguntas o problemas elige para introducir un tema, cómo identifica las ideas previas de sus estudiantes y cómo esto contribuye a la generación de un nuevo conocimiento (Garriz et al., 2008; Talanquer, 2004).

Desde la visión de las prácticas o competencias claves de los docentes para su trabajo en el aula, autores han sugerido que las motivaciones, intenciones o atención docente tienen una gran influencia en las decisiones que toman y las acciones que implementan en el aula (Russ, 2018). Russ (2018) ha destacado diferentes enfoques en la caracterización de la atención docente, la que puede estar: en los objetivos docentes, en los niveles de atención del profesor, en el conocimiento utilizado por el docente o bien en las prácticas discursivas empleadas para escuchar el pensamiento de los estudiantes. Este autor sugiere que, a pesar de la diversidad de nomenclaturas utilizadas en los estudios para analizar la atención docente, todos ellos apuntan a elementos críticos en la atención de un maestro. Concluyendo que finalmente lo relevante es considerar los mensajes que los profesores envían implícitamente a los estudiantes (es decir, qué elementos de conocimiento, formas de razonamiento o prácticas que destacan).

Uno de los trabajos que en la literatura sobre análisis de discurso en el aula destaca por considerar las intenciones docentes, así como también las interacciones de aula y características dialógicas del discurso es el desarrollado por Mortimer y Scott (2002). Los autores proponen cinco dimensiones críticas en el análisis de las interacciones y los significados construidos en el aula de ciencias: enfoque comunicativo, intenciones del profesor, contenido, patrones de interacción e intervenciones docentes. El enfoque comunicativo de un maestro se caracteriza en un continuo que puede transitar desde un enfoque interactivo/dialógico a un enfoque no interactivo/autoritario (Mortimer y Scott,2002). Cuando los profesores adoptan un enfoque dialógico, exploran las ideas de los estudiantes y crean oportunidades para que los estudiantes construyan su comprensión a través del diálogo. Mientras que al adoptar un enfoque autoritario, presentan un punto de vista específico que se espera que los estudiantes entiendan y acepten como tal.

En el marco de la perspectiva dialógica/interactiva, estudios han analizado los patrones de interacción o movimientos de habla en que los docentes desarrollan durante su discurso. Mediante el uso del lenguaje los docentes en el marco dialógico actúan como mediadores durante el proceso de aprendizaje, creando o limitando las oportunidades para el desarrollo del razonamiento de los estudiantes (Mercer, 2004; Michaels et al., 2008). Los estudios en este campo han revelado el papel central que desempeña el diálogo en el aula para dar forma al aprendizaje (Dawes, 2004; Maine & Hofmann, 2016; Mercer & Howe, 2012; Michaels & O´Connor, 2015; Rojas-Drummond, Torreblanca , Pedraza, Vélez, & Guzmán, 2013).

Estudios apuntan a que los movimientos de habla de los docentes parecen tener una gran influencia en el nivel de razonamiento manifestado en un aula (Michaels & O´Connor, 2015). Tipos específicos de conversación han sido reconocidos como mejores para fomentar la construcción del conocimiento y el razonamiento científico. Estas conversaciones denominadas " *accountable talk* " (Wolf, Crosson, & Resnick, 2006) o *"exploratory talk"* (Mercer, 2004) involucran a los estudiantes en el intercambio de ideas basadas en hechos explícitos, estableciendo relaciones coherentes, para luego construir conclusiones razonables (Michaels, O ' Connor, & Resnick, 2008).

Desarrollar esta tarea por parte de los docentes requiere de un conocimiento de las formas en que los estudiantes razonan en la clase de ciencias, qué ideas identifican, qué elementos son considerados en las relaciones que establecen y cómo estas relaciones progresivamente se alinean a modelos causales que les permitan elaborar explicaciones. Sin duda, esta tarea se encuentra incompleta si no existe evidencia de estas formas de razonamiento, o si se mantienen en la invisibilidad en el aula.

2.4 Propiedades coligativas como contexto de estudio

Estudios en el campo del razonamiento que subyace la tarea de construcción de explicaciones, dan cuenta de que esta habilidad debe ser contextualizada en un tópico específico, pues de ello depende el desempeño de los estudiantes (Weinrich & Talanquer, 2016). En este estudio hemos considerado como contexto disciplinar el tema de propiedades coligativas, con el objetivo de aportar evidencia sobre el razonamiento utilizado en la generación de explicaciones asociadas al comportamiento de soluciones acuosas.

Abordar explicaciones en este tópico permite explorar las formas en que los estudiantes integran la teoría cinético molecular en el contexto de una mezcla. Teoría que generalmente se asocia a representaciones de sustancias puras. Por otro lado, este tópico considera un conjunto de propiedades que no dependen de la naturaleza de las entidades involucradas en la mezcla, ni de cambios en las propiedades de las sustancias. Como señala Talanquer (2010), las propiedades coligativas son producto de cambios en la probabilidad de transferencia aleatoria de las partículas de soluto y solvente en la mezcla, lo que produce que el equilibrio en el proceso de intercambio de las partículas entre las fases involucradas suceda a temperaturas o presiones distintas en relación al solvente puro.

Dificultades asociadas la costrucción de explicaciones en el tópico de disoluciones y sus propiedades han sido reportadas en estudiantes de pregrado. En este contexto se evidencia que la mayoría de los estudiantes explican el cambio en el punto de congelación de una solución acuosa en función del tiempo, señalando que el soluto “retrasa” el punto de congelación (Çokadar, 2009), además de construir explicaciones aditivas, considerando las propiedades físicas y químicas de las sustancias y mezclas como resultado de un promedio de las propiedades de sus componentes (Talanquer, 2010).

Los antecedentes presentados sobre investigaciones en torno a las formas de razonamiento que subyacen a las explicaciones, los tipos de causalidad que se desarrollan en la escolaridad, los niveles de sofisticación del razonamiento químico propuestos en la literatura y la selección del tópico de descenso del punto de congelación como contexto de esta investigación, nos permite plantear los objetivos que guían el estudio en la siguiente sección.

2.5 Objetivos de Investigación

2.5.1 Objetivo General

Caracterizar el razonamiento individual y colectivo que subyace a la construcción de explicaciones en el aprendizaje de la química escolar.

2.5.2 Objetivos específicos

OE1: Identificar los tipos de razonamiento que subyacen a las explicaciones escritas construidas por estudiantes de enseñanza media al explicar el descenso del punto de congelación de una mezcla respecto del solvente puro.

OE2: Caracterizar de qué manera las intervenciones docentes modelan el razonamiento expresado en la clase de química al construir explicaciones sobre el descenso del punto de congelación de una mezcla respecto del punto de congelación del solvente puro.

2.6 Aspectos Metodológicos

Considerando la especificidad y profundidad que requiere la comprensión de los procesos de razonamiento que subyacen a las explicaciones elaboradas individual y colectivamente en la clase de química, esta investigación se posiciona en un paradigma de investigación cualitativa (Hernández, Fernández, & Baptista, 2010). Mediante una estrategia de muestreo por conveniencia (Flick, 2004; Hernández et al., 2010) se accedió a dos aulas con un total de 78 estudiantes guiados por una docente de química. Utilizando el método de estudio de caso (Sandín, 2003) analizamos las producciones escritas de cada uno de los participantes, además de las interacciones de aula, con el propósito de llegar a abstracciones concretas y singulares referidas a la muestra analizada, de las cuales podamos identificar patrones que nos permitan extraer lo que es generalizable a otras situaciones (Merriam, 1998; Miles & Huberman, 1994).

2.6.1 Contexto y participantes

La investigación se llevó a cabo en el contexto de un establecimiento educacional chileno de dependencia particular subvencionada de la Región Metropolitana. Los participantes correspondieron a 78 estudiantes pertenecientes a dos cursos (en adelante llamados secciones) de segundo año de enseñanza media y una profesora de química encargada de la asignatura en ambos cursos. Los datos se recolectaron en el contexto de la unidad de disoluciones en el tópico de propiedades coligativas. La clase observada correspondía a la propiedad coligativa de descenso del punto de congelación, de la cual se tomó registro audiovisual además de recolectar las producciones escritas de los estudiantes al inicio y al final de la lección.

2.7 Organización del compendio

La organización de este compendio se distribuye en dos artículos cada uno de los cuales desarrolla uno de los objetivos específicos propuestos en esta investigación. En la Figura 2.4, se muestra un diagrama que describe la organización de este documento en función de los momentos y producciones de la clase que fueron analizados. En un primer artículo presentamos los resultados del análisis de las producciones iniciales escritas de cada uno de los participantes del estudio. Los hallazgos de esta primera publicación permitieron cumplir con el objetivo específico 1.

En un segundo artículo se presenta la aplicación de la estrategia de análisis diseñada en una primera etapa a las explicaciones finales de los estudiantes. Además de investigar cómo las intervenciones docentes modelan los cambios en el razonamiento de los y las estudiantes durante la clase de química. El desarrollo de esta segunda fase permitió el cumplimiento del objetivo específico 2.

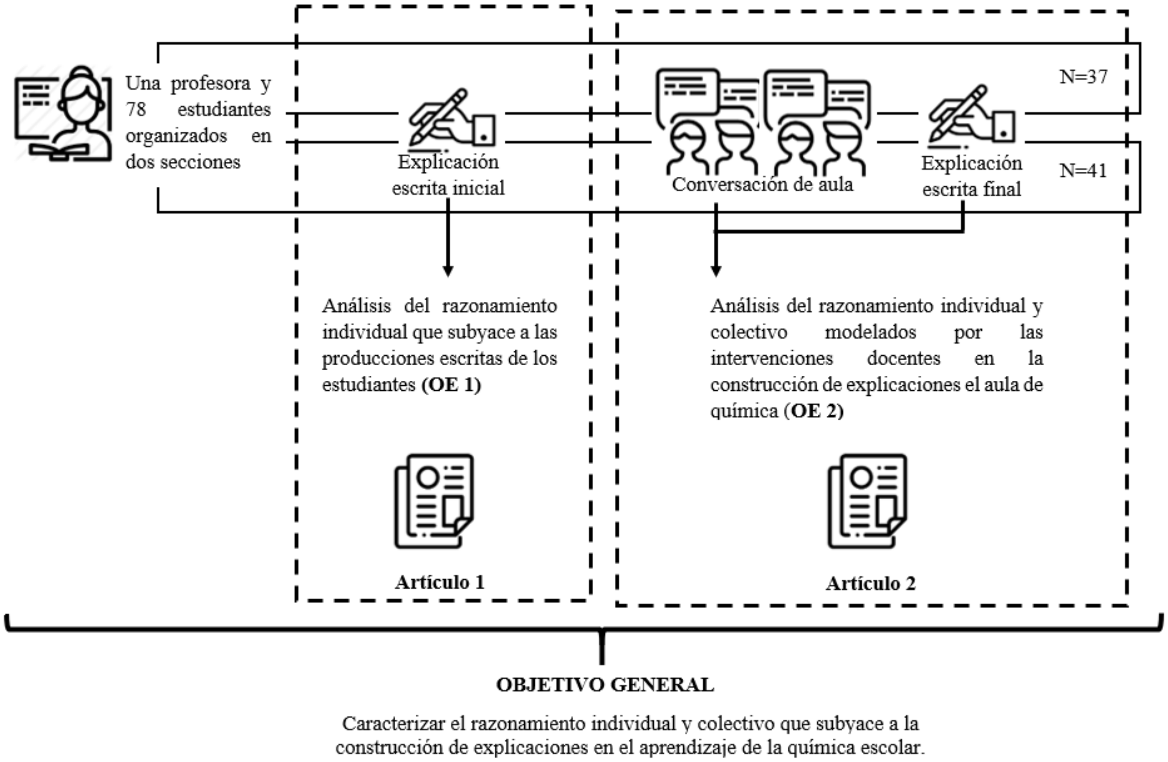

Figura 2.4. Organización del compendio de artículos.

3 Publicaciones

3.1 Artículo 1

Título: Using a mechanistic framework to characterise chemistry students´ reasoning in written explanations

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Using a mechanistic framework to characterise chemistry students' reasoning in written explanations

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The central goal of this research study was to characterise the different types of reasoning manifested by high school chemistry students when building initial written explanations of a natural phenomenon. In particular, our study participants were asked to explain why a mixture of water and alcohol works as an antifreeze. Data collected in the form of written explanations were analysed using a mechanistic reasoning framework based on the characterisation of system components (*e.g.*, entities, properties, activities, organisation) and paying attention to the causal models invoked by the participants in their explanations. Our analysis revealed that students at the same educational level construct a wide range of explanations for the same phenomenon that are indicative of different reasoning modes going from descriptive to relational to simple causal to emerging mechanistic. Although the explanations generated by students in our sample were not very sophisticated in terms of the causal models on which they relied, some participants were capable of generating mechanistic explanations using particulate models of matter. The framework for analysis introduced in this contribution can be of use to teachers and researchers in the characterisation of student reasoning.

Introduction

As a globalized society we face a variety of social, environmental and technological challenges. To successfully address them, we need to prepare citizens who can understand and reason about the impact that their decisions could have at the personal, community, and planetary levels (Bybee *et al.*, 2009). We require individuals who are able and have the disposition to critically analyse the information they receive, seek scientific explanations, and engage in evidence-based argumentation (National Research Council [NRC], 2013). These abilities require more than a basic understanding of the scientific content typically covered in school science curricula. They demand the integration of central ideas into coherent explanatory frameworks (Millar, 2006). This integration is favoured when students have multiple opportunities to actively engage in building explanations of relevant phenomena (Windschitl *et al.*, 2018). Fostering students' ability to construct scientific explanations is thus seen as critical in the development of functional scientific literacy (Ryder, 2001; Bybee *et al.*, 2009).

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The aforementioned educational goals are shared by Chile, the country where the present study was conducted. The Chilean school curriculum highlights the importance of developing students' ability to engage in science practices such as building explanations. However, national and international standardized test results show that the educational system falls short of meeting this goal. According to these data, Chilean students demonstrate low performance in using their scientific knowledge to explain relevant phenomena (Agencia de Calidad de la Educación [ACE], 2015).

Studies about the nature of scientific explanations (Hempel and Oppenheim, 1948; Salmon, 1984; Machamer *et al.*, 2000) and students' ability to generate them (Talanquer, 2010; Braaten and Windschitl, 2011; Rottman and Keil, 2011; Yeo and Gilbert, 2014) are diverse. Some authors have focused on the structure of these explanations (Tang, 2016; Cabello, 2017); others have paid attention to the different functions that explanations serve (Gilbert *et al.*, 2000) or to the types of causal relationships that are established within them (Brewer *et al.*, 1998; Grotzer, 2003; Christidou and Hatzinikita, 2006; Talanquer, 2007, 2010). These different studies emphasize the importance of developing students' explanatory abilities but also reveal the multiple challenges in doing so.

In recent years, there has been increased interest in better characterising and fostering students' ability to generate causal mechanistic explanations (Grotzer, 2003; Russ *et al.*, 2008, 2009;

Becker *et al.*, 2016; Southard *et al.*, 2017; Talanquer, 2018). These types of explanations are a hallmark of scientific reasoning and students are expected to generate them using normative concepts and ideas (NRC, 2013). In this paper, we present the results of a study in which different frameworks for the characterisation of mechanistic reasoning were integrated and adapted to analyse students' written explanations in a secondary school chemistry class. Our goal is to illustrate how our approach can be applied to identify and characterise different levels of expressed causal reasoning in students' explanations. The proposed analytical framework should be useful to both educational researchers and teachers interested in advancing students' explanatory abilities.

Exploring causal reasoning

Engaging students in explanation creates opportunities for them to organise their ideas and build connections between concepts to make sense of systems and phenomena (Izquierdo and Aliberas, 2004). The specific connections or relationships that students establish between concepts and ideas are indicative of their reasoning sophistication. A variety of authors have explored the nature of these relationships seeking to characterise different types of reasoning (Tamir, 1991; Assaraf and Orion, 2005; Sevian and Talanquer, 2014; Becker *et al.*, 2016; Weinrich and Talanquer, 2016). These studies have shown that student reasoning may range from merely descriptive to mechanistic for individuals at the same educational level.

The level of sophistication or complexity in reasoning has been characterised by analysing the causal models that students deploy along different dimensions, such as the type of agency, the interaction patterns, the level of certainty in the causal connections, and the mechanism that are invoked (Grotzer, 2003; Perkins and Grotzer, 2005). Other authors have considered the number and level of integration of the different elements used in the reasoning process (Biggs and Collis, 1982; Brown *et al.*, 2010). The results of these types of investigations were adapted by Sevian and Talanquer (2014) to define a set of modes of reasoning corresponding to different levels of sophistication in student reasoning in chemistry going from descriptive to relational to linear causal to multi-component. The latter type of reasoning shares many of the characteristics that other authors attribute to mechanistic reasoning.

Mechanistic explanations are characterised by the detailed descriptions of the processes that are responsible for the behaviour of a system of interest (Grotzer, 2003). These types of explanations are based on the identification of relevant entities in a system, their properties and interactions, the activities in which they engage, and the patterns of organisation that they manifest (Machamer *et al.*, 2000). The activities and organisation of core entities are seen as causally responsible for the properties and behaviours of the system as a whole. Interest has grown in recent years in the analysis of mechanistic reasoning in different science fields and the exploration of how to foster its development in science classrooms. Several of these investigations have been carried out in the context of biology education (Machamer *et al.*, 2000; van Mil *et al.*, 2013; Southard *et al.*, 2017), but they have also recently emerged in the field of chemistry (*e.g.* Bhattacharyya, 2013; Becker *et al.*, 2016; Talanquer, 2018).

Distinguishing mechanistic reasoning from other types of causal reasoning may be challenging. Russ *et al.* (2008) proposed a framework for recognizing student mechanistic reasoning when engaged in scientific inquiry. This framework for discourse analysis was developed by adapting accounts of mechanism from the philosophy of science (Machamer *et al.*, 2000). Within this framework, mechanistic explanations are distinguished from other types of explanations by the description and analysis of the spatio-temporal organisation of the entities that comprise a system. Students are capable of building these types of explanations although the mechanisms that they propose may not align with accepted scientific accounts. The discourse analysis framework for recognizing mechanistic reasoning introduced by Russ *et al.* (2008) includes seven categories of analysis: (1) describing the target phenomenon, (2) identifying setup conditions, (3) entities, (4) activities, (5) properties of entities, (6) organisation of entities and (7) chaining.

In this study, we integrated and adapted different approaches to the characterisation of students' causal reasoning (Grotzer, 2003 ; Russ *et al.*, 2008; Sevian and Talanquer, 2014) in our analysis of written explanations. Our analytical approach can be used by both teachers and researchers to analyse students' explanations and characterise the level of causal sophistication in their expressed reasoning.

Research question and rationale

This work is part of a larger qualitative research project directed at characterising the types of explanations built by secondary school students. This particular study centred on the analysis of students' explanations of freezing point depression of aqueous solutions and was guided by the following research question:

• *What different types of reasoning manifest in students' explanations of the phenomenon under analysis?*

The focus on explanations of freezing point depression was partly determined by constraints imposed by the educational setting in which the research took place. Data collection had to be orchestrated with a teacher who was following a pre-set curriculum and had limited flexibility in her schedule for our investigation. Our choice was also influenced by the nature of the scientific explanations often built to make sense of colligative phenomena. These explanations are constructed using a simple particulate model of matter without referring to specific physical or chemical properties of main system components. In these explanations, colligative properties are seen as emerging from changes in the probability of transfer of solvent particles from one phase of matter to another (Talanquer, 2010). Thus, although the invoked model is simple the appropriate mechanistic explanation is quite sophisticated. We hypothesized that these characteristics would increase opportunities to observe a wide range of student explanations. This hypothesis was also informed by existing research on students' difficulties understanding colligative effects. These studies have shown that students often build alternative explanations using an additive *versus* an emergent reasoning framework (Talanquer, 2010), and that they tend to misinterpret the effect of the solute by assuming that it changes the time it takes for the phase change to occur rather than the temperature of the transition (Çokadar, 2009).

Methodology

Context and participants

This research was based on the analysis of the explanations generated by 78 students (39 females; 39 males) enrolled in two 10th grade chemistry classes taught by a teacher who volunteered to participate in the study. Study participants attended a Chilean private-subsidized secondary school. Data were collected as part of a lesson on the topic of freezing point depression. The objective of this lesson was to explain the relationship between freezing temperature and solution concentration. All participants gave their consent to participate in the study. As students were underage, consent was also provided by their legal guardians.

Research instrument

Our research probe consisted of an in-class activity based on a hypothetical scenario involving the use of automotive antifreeze. The task asked students to explain in writing why an antifreeze mixture had a lower freezing point than the pure solvent. Students were also asked to create drawings to support their explanation, with the expectation that their drawings could provide additional insights into students' thinking about how the phenomenon happened. Research suggests that written responses often focus on dynamic aspects of a phenomenon while pictorial representations emphasize structural features (Akaygun and Jones, 2014). The English version of the task is presented below. Translations from Spanish of this question and associated student responses presented in the Findings section were completed by the third author of this paper who is fluent in both languages. Nuances in the original text may be lost in translation:

Ignacia is about to embark on a trip with her family. They will travel to an area near a mountain range where below 0 °C temperatures are expected. After packing and loading the car, Ignacia and her family stop by a gas station. The clerk recommends that they take a bottle of antifreeze with them. Ignacia remembers that her chemistry teacher explained that antifreeze is a mixture of water and alcohol used to prevent water from freezing in the car's engine. Inspired by this thought, Ignacia tells her family what her teacher said. Intrigued, Ignacia's brother asks her: why is it that water doesn't freeze when alcohol is added? Place yourself in Ignacia's shoes: how would you explain to your brother why the mixture of water and alcohol works as an antifreeze? (Create a drawing in the provided box to support your explanation).

Data collection

Students' explanations were collected at the beginning of the lesson on freezing point depression. This lesson followed a class in which the topic of boiling point elevation had been introduced. The teacher handed a paper copy of the research probe to each student and read it aloud with them. Students were given 10 minutes to complete the assignment. The teacher did not intervene during this time other than to ensure each student completed the task individually. A total of 78 worksheets were collected but only 75 of them included an actual response.

Data analysis

Students' written explanations and associated drawings were analysed using a constant comparison method looking for emerging patterns in student reasoning (Miles and Huberman, 1994; Creswell, 2013). We adopted a qualitative interpretative perspective (Sandín, 2003) in the characterisation of the different components present in students' explanations and their relationships. To answer our research question, we analysed the data at two different levels. First, we identified core explanatory components and then we sought to make explicit the relationships among them to evaluate the complexity of students' reasoning.

(a) Identification of explanatory components: to complete this part of the analysis, we adapted the discourse analysis framework proposed by Russ *et al.* (2008) to characterise students' reasoning. An initial coding system was developed based on the seven categories of analysis suggested by these authors. These categories were applied in the analysis of each student's explanation. The presence of more of these categories in a single explanation was often indicative of a more advanced response. This coding scheme was tested by five different researchers who coded 3% of the collected explanations. Based on the results of this first analysis, the coding scheme was revised to adjust it to the nature of the collected data. Three of the initial categories (description of target phenomenon, identification of set up conditions, and chaining) were eliminated as they did not help differentiate between explanations or were not significantly present in the explanations generated by our study participants. The revised coding matrix was applied by two of the authors of this study to 40% of the sample and individual codes were then compared and discussed. Disagreements were resolved through several rounds of discussion which led to adjustments in the coding scheme. The final scheme was applied by the first author of this paper to analyse the remaining explanations in the sample. The scheme included the following categories of analysis:

(1) *Entities* (E_x): Material components of the system. They may include macroscopic (*e.g.*, substances) or submicroscopic (*e.g.*, particles) components.

(2) *Properties* (P): Characteristics of the entities that are relevant in building the explanation. They may be general or specific. Some examples include freezing point and mass. The analysis identifies the entity associated with the cited property and the type of property that is invoked.

When water and alcohol are mixed the solution remains in its liquid state when temperatures are lower than the freezing point of the pure solvent (water). This happens because there is a change in the arrangement of the water molecules when alcohol is added to the solution. The alcohol molecules interfere with the organization of the water molecules into a solid form and the effect is larger when more solute is added. Because of this, the temperatures have to be lower than the freezing point of the pure solvent in order for the mixture to freeze. The more solute is present the lower the new freezing temperature will be.

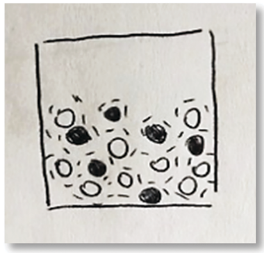


Fig. 1 Hypothetical response to our research probe. It corresponds to Level IV (Emerging Mechanistic) in our analysis.

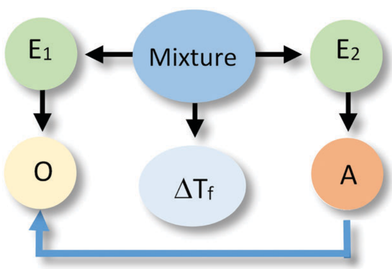


Fig. 2 Reasoning diagram corresponding to the explanation in Fig. 1. The blue arrow represents the causal relation between the activity (A) of Entity 2 (E_2, alcohol) and the organization (O) of Entity 1 (E_1, water) assumed to cause the change in the freezing point. The symbol ΔT_f represents freezing point depression.

(3) *Activities* (A): Actions/interactions cited as causing changes to entities and/or to the whole system. These activities establish explicit cause–effect relationships. The analysis identified what entity is involved in the action or interaction, and, the type of activities (there may be more than one) invoked in the explanation.

(4) *Organisation* (O): This category refers to the spatial-temporal location of the entities during a determined activity and its causal connection to the properties or behaviour of the system.

(5) *Representation* (R): This category refers to the extent to which the drawing provides additional insights into student reasoning. Drawings were used in our analysis to identify other explanatory components not present in the written explanations, such as entities or organisation.

(b) Identification of relationships among components: once the different explanatory components in each explanation were identified, their relationships were mapped into a "reasoning diagram." The construction of these diagrams was informed by existing work on causal models and relationships (Grotzer, 2003). These types of diagrams allowed us to more easily differentiate between types of reasoning. This evaluation was guided by the scheme proposed by Sevian and Talanquer (2014) to characterise different modes of reasoning. This scheme was adapted considering the specific nature of our data. In particular, we assigned the different explanations to four different levels: Level I (Descriptive); Level II (Relational); Level III (Simple Causal); and Level IV (Emerging Mechanistic), characterised in detail in the Findings section.

To illustrate our process of data analysis, we present an example of its application using the hypothetical written response included in Fig. 1. Our analysis of this explanation in terms of explanatory components reveals references to two different *entities* (water particles and alcohol particles) engaged in different *activities* (*e.g.*, getting arranged, interfering in the arrangement). Additionally, the explanation refers to the *organisation* of water particles, and the effect

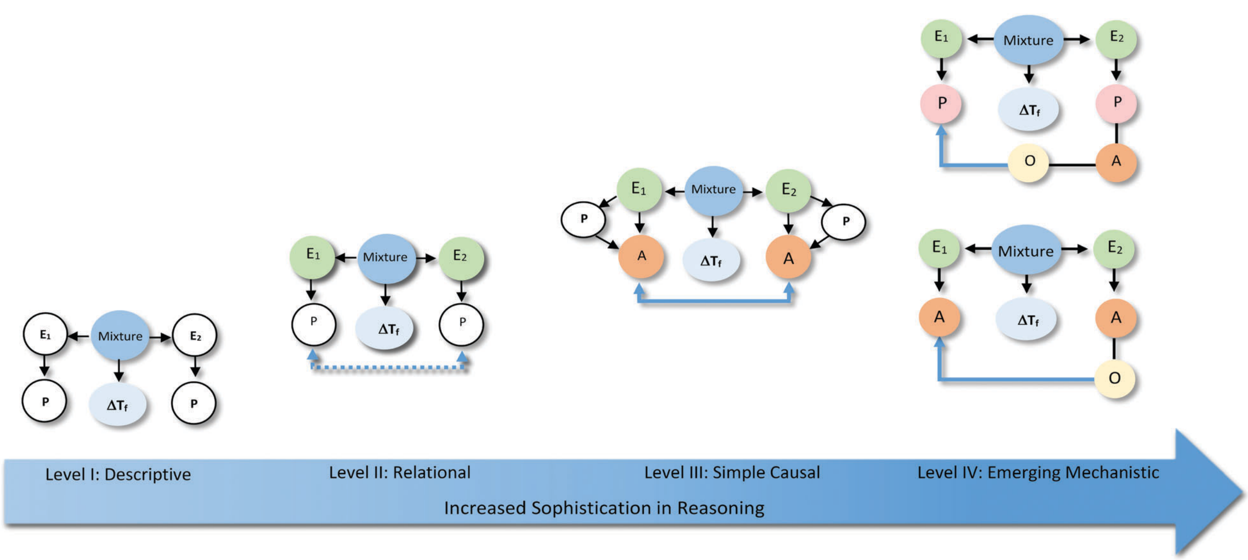


Fig. 3 Representative reasoning diagrams for the four major levels of reasoning identified in the study. Different colors are used to represent different components in an explanation. Blue dotted arrows in Level II diagrams are used to represent non-causal associations between entities or their properties, while solid blue arrows are used to represent actual causal links. Circles in black and white represent elements that may or may not be present in the explanations at any given level.

of alcohol particles in such organisation, in making sense of the phenomenon observed. No reference to specific *properties* of the entities in the system is made in the construction of this explanation. The drawing included in Fig. 1 is consistent with the associated written response but does not add to its explanatory content. This example is representative of what we observed in the analysis of the explanations of students in our sample. In general, drawings only provided additional insights into student reasoning for some of the explanations at Level IV (Emergent Mechanistic) in our analysis.

The identification of relationships between explanatory components in the hypothetical explanation is summarized in the reasoning diagram in Fig. 2. In this reasoning diagram we make explicit that two entities in the mixture, E_1 (water) and E_2 (alcohol) are identified in the explanation. An activity (A) of entity E_2 is assumed to affect the organisation (O) of entity E_1 as indicated by the direction the arrow from A to O.

In the following section we summarize the core findings of our analysis. We only describe patterns of reasoning observed in no less than two students' responses. The described patterns encompass 96% of the 75 explanations that were analysed.

Main findings

The analysis of our study participants' explanations of freezing point depression led us to the identification of 15 different patterns in student reasoning using the analytical approach described in the previous section. Some of these patterns had core characteristics in common that were used to arrange them into four major categories reflecting different levels of sophistication in student reasoning. Representative reasoning diagrams for each of these four categories of reasoning are presented in Fig. 3 arranged in order of increased sophistication. Level I (Descriptive) includes responses that are descriptive in nature and limited to restating the phenomenon in different words. Explanations in Level II (Relational) rely on simple associations between properties of the main entities in the system. In Level III (Simple Causal), explanations are based on the activities of one or more of the system's entities, while explanations in Level IV (Emerging Mechanistic) refer to an organisation of entities and activities in space and time to make sense of the phenomenon.

The percentage of explanations in each of the four major levels of reasoning identified in our study is represented in Fig. 4. Close to 15% of students' responses were at the descriptive level (Level I), while the largest percentage of the explanations (45%) generated by study participants included simple associations between properties of the main components and the system's behaviour (Level II). Explanations at Level III were found in 28% of the responses and included reasoning that causally linked the actions of systems' components to the change in the freezing temperature of the solution. Only 12% of the explanations generated by students were classified at Level IV and referred to some type of mechanism involving the spatio-temporal organisation of entities and activities. A more detailed description and analysis of characteristic explanations at each level of reasoning is presented in the following paragraphs.

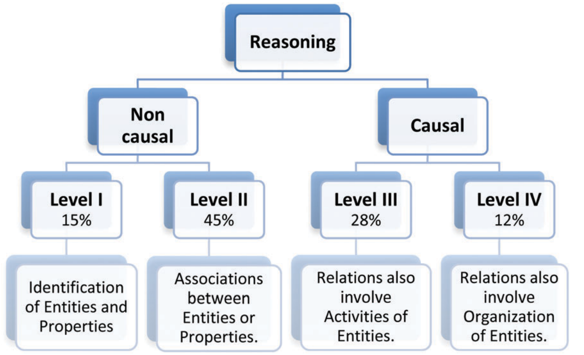


Fig. 4 Main types of reasoning manifested in the explanations generated by our study participants.

Level I: descriptive

At this first level we placed written answers that were not actual explanations but rather re-descriptions of the phenomenon to be explained (15%). Responses in this group could include references to the properties of system components (water or alcohol), but without a clear causal link between those properties and the phenomenon under analysis. Examples of responses at this level of sophistication are included in Table 1, together with their associated reasoning diagrams. Responses at Level I were separated into two subgroups based on whether students identified properties of any of the entities in the system. At the L1Sa sublevel, responses referred to the targeted behaviour (anti-freezing) as an intrinsic property of the system (water–alcohol mixture). These types of answers could allude to different system components (see example i in level L1Sa in Table 1) but did not refer to any specific properties of these entities that led to the phenomenon under study. Students' descriptions at this level were intentional in the sense that alluded to the purpose of the mixture without explaining why the solution worked in such a manner.

Responses at the sublevel *L1Sb* involved the recognition of different components present in the system as well as references to properties of those entities (*e.g.*, water easily freezes, alcohol has greater resistance) assumed to be responsible for the observed phenomenon (lower freezing point). However, there was no discussion of how these entities or their properties produced the phenomenon.

Level II: relational

This second level of sophistication referred to specific entities, some of their properties, and relationships between them to make sense of the phenomenon. These relationships included unidirectional effects of one entity on another (L2Sa), of the property of one entity over the other entity (L2Sb), of a property of one component over a property of the other (L2Sc), as well as bidirectional effects between properties of the two components (L2Sd). Specific examples of these different ways of reasoning are included in Table 2 together with their corresponding reasoning diagrams.

In explanations at the sublevel L2Sa, students thought of the alcohol (E_2) as an active agent that caused a change to the water

Table 1 Reasoning diagrams and associated representative responses at Level I

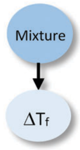
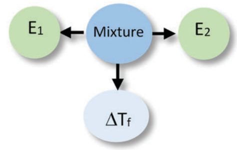
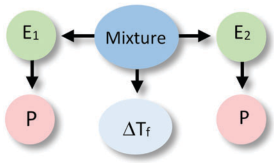
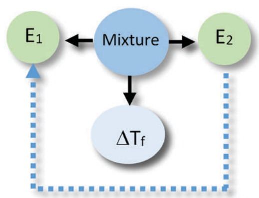
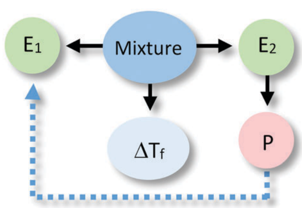
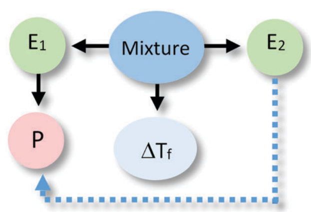
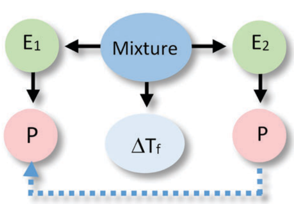
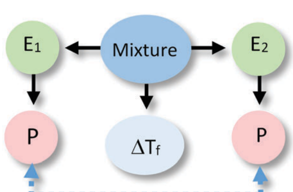
Level	Reasoning diagrams and representative explanations	
L1Sa	 (i) *It is a mixture used to unfreeze. It is added so that it does not freeze.* 3 students (4%)	 (ii) *Because water is the solvent and alcohol is the solute. The reaction causes the solution not to freeze given the smaller amount of alcohol compared to water (solvent).* 2 students (3%)
L1Sb		I would explain this to my brother by saying that the anti-freezer is necessary because of the below zero temperatures, and water is a bad anti-freezer because it easily freezes at low temperatures. Alcohol has other properties that should have a greater resistance given that it is a chemical compound. 6 students (8%)

Table 2 Reasoning diagrams and representative responses at Level II. Percentages indicate the relative distribution of explanations (34 total) in this group. Dotted blue arrows are used to represent non-causal associations between entities or their properties

Level	Reasoning diagrams and representative explanations	
L2Sa		*One of the reasons why it doesn't freeze is because of the properties of the mixture. It is also because the solvent (water) is somehow affected by the solute (alcohol), delaying the freezing process.* 2 students (3%)
L2Sb	 (i) *Because the alcohol has components that prevent water from freezing.* 10 students (13%)	 (ii) *I suppose water only freezes at a certain temperature below 0 °C and that the anti-freezer with alcohol has a low lower freezing point than pure water. So the alcohol is the solute that in this case affects the water's freezing point.* 7 students (9%)
L2Sc		*I believe water doesn't freeze because the alcohol has a lower freezing point and when mixed with water it changes its components causing its freezing point to be lower, but not as much as that of the pure alcohol.* 13 students (17%)
L2Sd		*Because the alcohol has a certain amount of degrees that together with those of water reaches a middle point where they prevent water in the car engine from freezing and keep the same degrees.* 2 students (3%)

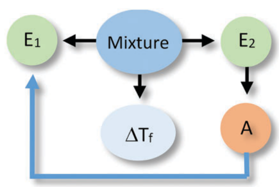
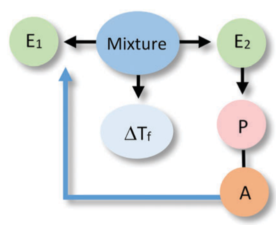
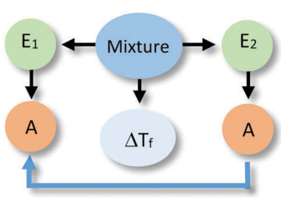
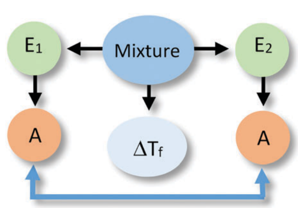
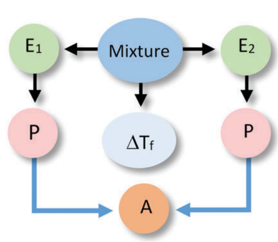
without detailing how the action occurred. At sublevel L2Sb, explanations referred to the properties of one of the entities in the system as responsible for the effect. These types of explanations could refer to a property of the alcohol that interfered with water's freezing process (example i in L2Sb in Table 2) or to the alcohol directly acting on a property of water (*e.g.*, water's freezing point, as in example ii in L2Sb in Table 2). Similar to explanations in sublevel L2Sa, the relationships invoked were unidirectional with the alcohol acting as the change agent.

Explanations at the sublevels L2Sc and L2Sd were characterised by their reference to the properties of both entities to explain the observed phenomenon. In the former case (L2Sc), a unidirectional relationship was established with a property of the alcohol (*e.g.*, lower freezing point) affecting a property of water. At the sublevel L2Sd, the properties of both components were seen as responsible for the change in an additive manner (*i.e.*, the properties of the mixture result from the combination of the properties of the components).

Level III: simple causal

Close to 28% of all explanations were located at the third level of sophistication. These explanations incorporated activities of one or more components of the system as part of their rationale (see Table 3). These activities involved direct action of one entity over the other or were mediated through specific properties of the components. These explanations included more details on the actions of a causal agent and more explicit causal relationships, going from unidirectional relations to cases of mutual

Table 3 Reasoning diagrams and associated representative responses at Level III. There were three explanations (4%) in this group that were unique in terms of their reasoning pattern (not found in more than one explanation). Blue arrows represent major causal links

Level	Reasoning diagrams and representative explanations	
L3Sa		*They act as anti-freezers because when mixing water and alcohol, the alcohol increases the temperature and prevents water from reaching its freezing point, this is, the alcohol prevents it from freezing.* 4 students (5%)
L3Sb		*When two things get together (water and alcohol) create a solution. For something to freeze the temperature has to go down and the alcohol doesn't allow this to happen because of the composition of the alcohol and its elements, the particles move around a lot and this causes them to get warm or something like that.* 3 students (4%)
L3Sc		*Because alcohol acts as a thermic catalyzer and helps to vapored water, so not get cold.* 3 students (4%)
L3Sd		*When mixing alcohol and water they cannot become a solution, resulting in a heterogeneous solution. The molecules of both substances would be in continuous movement trying to mix inside the car engine, preventing freezing from happening.* 4 students (5%)
L3Se		*I believe that when water and alcohol interact they produce an effect of more temperature or when both combine they produce more temperature because of the elements in each compound.* 4 students (5%)

causality as illustrated by the sequence of examples in Table 3. Explanations in this category were the most varied in terms of the observed reasoning patterns.

Explanation at the sublevel L3Sa alluded to an action or activity carried out by the alcohol (*e.g.*, increasing the temperature of the system) that affected the other entity. The relationship that was established was unidirectional with the alcohol as the causal agent. At the sublevel L3Sb, alcohol (E_2) was also seen as the active agent affecting the system (*e.g.*, making it warm) through an activity (*e.g.*, particles moving around), but this activity was linked to a property of the entity (*e.g.*, its chemical composition). The explanations located in L3Sc share the unidirectional relation with L3Sa and L3Sb. However, L3Sc refers to explanations that invoked activities of both entities, where the activity of alcohol produced changes in the activity of water.

In explanations at sublevels L3Sd and L3Se, both entities were considered to be engaged in an activity (*e.g.*, producing more temperature, particles moving around) responsible for the phenomenon, without one component being more active than the other. These types of explanations only differed in whether the activity was linked (L3Se) or not (L3Sd) to a specific property of the components.

Level IV: emerging mechanistic

The most sophisticated types of reasoning were placed in this level (12%). In these cases, explanations alluded to the spatio-temporal organisation of entities that are involved in activities. Representative examples are included in Table 4.

At the sublevel L4Sa, explanations referred to an activity of alcohol (*e.g.*, acting as a barrier to low temperatures) linked to the spatial organisation of alcohol particles surrounding the water particles. In this case, the organisation of entity E_2 affected an E_1 activity (*e.g.*, preventing water from freezing). In explanations of type L4Sb, the activity of E_1 is linked to a property of this entity (*e.g.*, alcohol has a higher freezing point than water). In both cases, causal relationships are unidirectional with the alcohol acting as the causal agent.

The reference to spatio-temporal organisation of entities in written explanations at Level IV was often complemented by the visual representations present in students' drawings. In particular, students' representations provided additional information about how students thought alcohol acted as a barrier, protecting or hindering water from freezing.

Agency

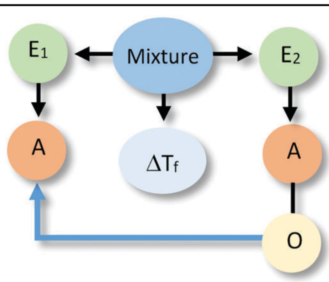
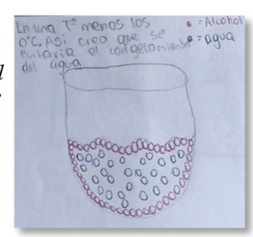
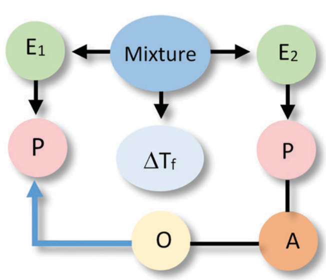
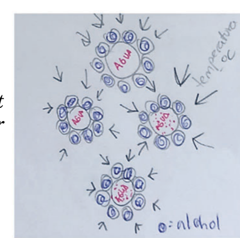
Many of the explanations generated by our study participants invoked simple relationships in which an active agent, typically the alcohol through its direct action, due to one of its properties, or by its spatial organisation affected the properties or behaviour of water or the solution. Although causal explanations formally appeared at Level III in our classification, the reference to alcohol as an active agent was present in explanations across Levels II through IV. In these different cases, alcohol was described as taking on one of the four roles described below. In each case, we indicate the percentage of the total responses in the category:

(a) Alcohol as a barrier or insulator (20%): this type of attribution was observed in explanations in Levels II, III and IV. In Level II, students more commonly referred to alcohol as an insulator while in Levels III and IV, the reference to a barrier was more frequent. Explanations at Level IV provided more detailed accounts of how alcohol actually prevented water from freezing. The following excerpts illustrate these different ways of reasoning:

• *The alcohol acts as a temperature insulator for water. (L2)*

• *Because when water is a pure solvent it is more vulnerable to phase changes, because nothing prevents its molecules from ordering.*

Table 4 Reasoning diagrams and associated representative responses at Level IV

Level	Reasoning diagrams and representative explanations		
L4Sa		*Maybe because when combining the alcohol with the water it causes the alcohol to become like a barrier, preventing water from freezing because it prevents the below zero temperatures from affecting the water in the car engine.* 7 students (9%)	
L4Sb		*I believe that the alcohol surrounds the water molecules, preventing the temperature from affecting them. I also believe that the alcohol has a freezing point much higher than that of water and because it surrounds it, it is more difficult for the cold to reach the solidification point.* 2 students (3%)	

But when adding alcohol, the water molecules are blocked by the alcohol that prevents their phase change. (L3)

• *Maybe because when combining the alcohol with the water it causes the alcohol to be like a barrier, preventing water from freezing because it prevents the below zero temperatures from affecting the water in the car engine.* (L4)

(b) Alcohol as a source of energy (13%): this type of agency was found in explanations at Levels II and III. Students at Level III were more likely to refer to the movement of particles as responsible for the observed phenomenon. Consider the following examples:

• *They act as an anti-freezer because the components in the alcohol cause the temperature of water to raise so water doesn't freeze.* (L2)

• *Because the alcohol generates movement in the water particles causing them not to freeze and then it causes it to evaporate because of the properties of the alcohol.* (L3)

(c) Alcohol as freezing retardant (12%): in these cases, study participants tended to think of freezing point depression as involving longer times to freeze. In these cases, it was difficult to determine whether students thought of the antifreeze as only affecting freezing time or implicitly assumed that lower freezing temperatures would be reached in longer times. These types of explanations were observed in explanations at Levels II and IV as illustrated below.

• *Pure water freezes faster because there is no solute in it, but in the anti-freezer there is a solute that prevents or delays the freezing of water*. (L2)

• *The solution takes longer to freeze because it has different components and it takes longer to get ordered to freeze.* (L4)

(d) Alcohol as an agent that changes water (5%): in this case, alcohol was seen as an agent that somehow changed the form or composition of water. These types of responses were found in explanations at Levels II and III. For example:

• *Alcohol is a substance different from water causing it to change its form to defend itself from the cold.* (L2)

• *The particles of alcohol affect those of water so that water could not freeze, it affects its composition.* (L3)

Discussion

The central goal of our research was to characterise the different types of reasoning manifested by high school chemistry students when building initial written explanations of a natural phenomenon. In particular, our study participants were asked to explain why a mixture of water and alcohol works as an antifreeze. Our analysis revealed that students at the same educational level construct a wide range of explanations for the same phenomenon that are indicative of different reasoning modes ranging from descriptive to relational to simple causal to emerging mechanistic. These modes of reasoning correspond to different levels of sophistication in causal thought and were characterised by paying attention to both the system components (*i.e.*, entities, properties, activities, organisation) and the causal models invoked by the participants in their explanations. Our analytical framework proved to be a productive tool in the identification and characterisation of differences in expressed student reasoning.

The majority of the explanations built by the students in our sample were based on simple associations between system components (relational reasoning), and close to 50% of the participants thought of alcohol as the active causal agent responsible for the phenomenon. The prevalence of this type of "centralized" view of causality in students' explanations has been highlighted by a variety of authors in previous studies (Resnick, 1994; Grotzer, 2003; Talanquer, 2010). Past studies have also shown that the types of explanations that students build is influenced by the nature of the question they are facing (Gilbert *et al.*, 2000; Talanquer, 2010; Sevian and Talanquer, 2014). Gilbert *et al.* (2000) have proposed six types of explanations based on the task or question to be answered: contextualizing, intentional, descriptive, interpretative, causal, and predictive. In our case, students were expected to generate causal explanations. However, less than half of our study participants actually built them.

A majority of the students in our sample generated non-causal accounts at Levels I (Descriptive) and II (Relational) in our characterisation. Explanations at Level I included simple re-descriptions of the targeted phenomenon with or without recognition of the entities present in the system and their relevant properties. Most of these explanations were intentional in nature (Gilbert *et al.*, 2000), focused on highlighting the role of the antifreeze in the car engine. Explanations at Level II recognized relevant entities in the system and some of their properties, establishing either unidirectional or mutual relationships between them. The different types of relationships present in explanations at Level II can be seen as indicators of emerging causality in student reasoning (Grotzer and Perkins, 2000). At this level, students recognized relevant components in a system and linked their presence, or their properties, to the phenomenon under analysis. There was, however, no attempt to build actual causal links between them. Instead, students often applied an additive schema in which the freezing point of the solution was seen as resulting from the average of the properties of the two entities in the mixture. Reliance on an additive schema to explain and make predictions about the properties of chemical systems has been reported previously in the chemistry education research literature (Talanquer, 2008, 2010).

Explanations at Levels III (Simple Causal) and IV (Emerging Mechanistic) involved different forms of relational causality in student reasoning, including simple linear causality and mutual causality (Grotzer and Perkins, 2000). Examples of simple linear causality were observed in explanations at Levels III and IV, while cases of mutual causality were only present in explanations at Level III. Student reasoning in explanations at Level III invoked activities of relevant entities as core components when explaining freezing point depression. In explanations at Level IV (Emerging Mechanistic), the spatio-temporal organisation of alcohol particles played a central role in justifying the observed phenomenon. Although these latter forms of reasoning were mechanistic in nature, they were not aligned with accepted scientific accounts. In non-normative manners, students often attributed central agency to the alcohol (or to the alcohol particles) which was frequently conceived as acting as a barrier or a retardant to the freezing of water, or as a source of energy in the system. Similar forms of causal attribution have been described in past investigations of students' understanding of colligative properties (Çokadar, 2009).

More than half of the students in our sample generated noncausal explanations, which may be indicative of low levels of knowledge integration that would limit their ability to apply scientific knowledge to everyday phenomena (Millar, 2006). Students who were capable of producing causal explanations in many cases referred to causal factors not aligned with accepted scientific accounts. These results are consistent with the findings of national and international standardized assessments that show low levels of performance in Chilean students' ability to explain natural phenomena (ACE, 2015).

Although the different types of reasoning represented by increased level of sophistication in Fig. 3 and 4 could be thought of as a progression in student learning, we cannot make that claim given the nature of our study. One could assume that the identification of major entities in a system and the recognition of their relevant properties are first and necessary steps in the process of learning to explain. The construction of simple associations between entities and properties may follow in the progression, and then move to identification of causal links mediated by interactions between entities and the activities to which they give place. Finally, the identification of spatio-temporal organisations would facilitate the elaboration of mechanistic accounts of the targeted phenomenon. Our findings do not support or contradict this potential learning progression. They just make explicit the range of reasoning types demonstrated by students and illustrate how they can be characterised in a systematic manner.

Implications

Our analytical approach elicited the wide range of reasoning modes that can be found among a group of students in a single class at the high school level. This diversity highlights one of the major challenges that teachers face in order to advance student thinking in science and chemistry classrooms. Helping all students develop their explanatory abilities is likely to require more individualized assessments, both diagnostic and formative, and instructional interventions. We believe that the framework for analysis introduced in this contribution can be of great use to teachers and researchers in the characterisation of student reasoning. The proposed approach focuses the attention on the identification of specific features in students' explanations and on the types of relationships between them. The representation of these elements in reasoning diagrams simplifies the characterisation of the levels of reasoning that are manifested.

We recognize that different task prompts may trigger responses that require the identification of additional features (*e.g.*, chaining) to characterise expressed reasoning. Nevertheless, a focus on the analysis of the core elements emphasized in our study could help teachers generate inferences about the types of reasoning that students express. Without formal coding, teachers could productively analyse student work by paying attention to (a) the specific reasoning features present in students' explanations (*i.e.*, entities, properties, activities, organisation), (b) the nature of the relationships between these elements that students highlight, and (c) the causal models (*e.g.*, linear, mutual) that they invoke.

Our findings indicate that although the initial explanations generated by many secondary school students may not be very sophisticated in terms of the causal models on which they rely, students at this level are capable of generating mechanistic explanations using particulate models of matter. Teachers should recognize and take advantage of this potential to advance students' explanatory abilities. This demands the creation of multiple opportunities for students to engage in explanation in the classroom, make their thinking visible, share ideas, and receive explicit guidance and feedback on how to build causal mechanistic accounts.

The results of our study suggest that chemistry students' initial explanations of targeted phenomena are likely to be non-normative, relying on intuitive assumptions about the properties and behaviours of chemical substances and processes (Talanquer, 2006, 2013; Taber and García-Franco, 2010). From this perspective, one could have expected that a phenomenon like freezing point depression may be attributed to the actions of an agent that actively hinders the freezing process. Teachers who want to develop their students' explanatory abilities should accept these types of non-canonical initial explanations rather than suppress them as soon as they are expressed. It is important for teachers to be responsive to alternative ideas, pressing students to further develop their thinking through causal mechanistic reasoning. Once different models are built in the classroom based on a set of diverse ideas, they can be compared and contrasted to evaluate their scope and limitations. It is in this evaluation process that teachers can more effectively intervene to introduce or move student thinking closer to the scientific accounts.

Advancing student thinking about colligative properties such as freezing point depression requires the construction of mechanisms that recognize the probabilistic nature of change at the particulate level. Students should be engaged in the analysis and discussion of how dynamic equilibrium is established in systems where competing processes take place (*e.g.*, melting and solidification). Once this understanding is developed, inferences about the effects of introducing perturbations in those equilibria (*e.g.*, adding a solute) should be easier to generate. Existing research shows that from a very young age, students possess cognitive resources that allow them to make sense of emergent phenomena and differentiate them from centralized (or directed) processes (Grotzer *et al.*, 2017).

Limitations

Our qualitative study focused on the analysis of the written explanations generated by a single group of 10th grade students working on a single task in a particular topic in the Chilean chemistry curriculum. Consequently, one should be careful in generalizing the scope of our findings. More investigations are needed to evaluate whether our analytical framework is robust and productive in the analysis and characterisation of the reasoning manifested by diverse types of students when asked to build causal explanations for a wide range of phenomena in different contexts. These types of studies could be strengthened by conducting individual interviews to gain more in-depth insights into student reasoning.

Conflicts of interest

There are no conflicts to declare.

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3.2 Artículo 2

Título: Investigating the effect of teacher mediation on student expressed reasoning

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Investigating the effect of teacher mediation on student expressed reasoning

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Understanding how chemistry teachers' interventions shape the reasoning that students express after a lesson is critical to support prospective and in-service teachers as they work with students´ ideas in the classroom. In this qualitative research study, we analysed changes in the reasoning expressed by 10th grade students in a Chilean school in their written explanations about freezing point depression before and after a lesson on the topic. We also investigated how a teacher's interventions shaped the type of reasoning expressed by participating students. Our findings revealed significant shifts in the types of explanations generated after the lesson. Although a large percentage of students expressed the same type of reasoning in their pre- and post-lesson explanations, there was also a significant number of students who transitioned towards simple causal reasoning in which explanations of the phenomenon were based on the activities of one or more of the system's entities. Analysis of teacher-student interactions during the observed lesson suggests that the teacher's mediation played a central role in the shift towards simple causal reasoning that was observed. The ways in which the teacher understood or decided to talk about freezing point reshaped her students' expressed reasoning, advancing their ideas in some cases but also constraining their thinking in others.

Introduction

Constructing explanations of every day phenomena requires the development of complex ways of reasoning (Grotzer, 2012; Grotzer, 2003). These types of reasoning demand identifying diverse and interacting causal relationships using appropriate scientific ideas to build explanations (Izquierdo & Aliberas, 2004). Engaging students in the construction and evaluation of explanations and arguments helps them better understand targeted concepts and develop their ability to use science practices in problem-solving and decision-making (McNeill & Krajcik, 2012). This work may be challenging, however, as student reasoning often relies on intuitive assumptions and heuristic rules that help reduce cognitive demand (Maeyer & Talanquer, 2010; Talanquer, 2014).

Although different types of explanations may be built to explain a phenomenon, it is common in many scientific fields, including chemistry, to build mechanistic accounts (Russ, Scherr, Hammer, & Mikeska, 2008). Mechanistic explanations are based on the characterization of the properties, interactions, activities, and spatio-temporal organization of core model components of a system assumed to be responsible for the phenomenon under analysis (Russ et al., 2008). Although students at all educational levels have the ability to build mechanistic accounts of natural phenomena (Becker, Noyes, & Cooper, 2016; Moreira, Marzabal, & Talanquer, 2019; Russ, Coffey, Hammer, & Hutchison, 2009), their reasoning needs to be scaffolded and opportunities need to be created to make student thinking visible and provide formative feedback (Aydeniz & Dogan, 2016; Russ et al., 2008).

In a recent study, we investigated the different types of reasoning initially expressed by 10th grade students in a Chilean school when asked to explain the phenomenon of freezing point depression in a mixture of water and alcohol (Moreira et al., 2019). Our study revealed that a majority of the participants built relational or simple causal explanations of this phenomenon. There were, however, students who generated mechanistic explanations involving the spatio-temporal organization of entities in the system. Although these explanations were non-canonical, they revealed students' ability to engage in mechanistic reasoning.

In this contribution, we analyse the types of explanations generated by the same group of students after a lesson designed by their teacher to help them understand freezing point depression. Our interest is twofold. On the one hand, we seek to characterize changes in student reasoning as a result of a teaching intervention. On the other hand, we want to analyse how a teacher's decisions and actions influenced student reasoning as expressed in a post-lesson task. The teacher who

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participated in our study was representative of secondary school teachers in Chile who are trained and directed to implement high-leverage teaching practices in their classrooms (Grossman, Hammerness, & McDonald, 2009). This teacher designed and implemented the observed lesson on her own, and was not aware of the specific goals of our research study. Our central goal in this part of the investigation is to provide insights into how a teachers' mediation influences expressed student reasoning. This type of analysis is needed to better support the work of teachers as they engage in the implementation of evidence-based teaching practices.

Teachers' mediation in science classrooms

The significant influence that teachers have on the learning process has been recognized for many years. Several studies have revealed critical characteristics of knowledge for teaching (Alvarado, Cañada, Garritz, & Mellado, 2015; Garriz, Nieto, Padilla, Reyes-cárdenas, & Velasco, 2008; Magnusson, Krajcik, & Borko, 1999; Shulman, 1987), as well as key teaching competencies and core practices (Aydeniz & Dogan, 2016; Bell & Cowie, 2001; Grossman et al., 2009; McDonald et al., 2014; Thompson, Windschitl, & Braaten, 2013; Windschitl, Thompson, Braaten, & Stroupe, 2012) that best foster meaningful learning. Research on knowledge for teaching using a pedagogical content knowledge (PCK) framework (Shulman, 1987) has helped characterize the types of specialized knowledge that effective teachers have, such as knowledge of curricular goals, discipline-specific instructional strategies, and students' difficulties in learning core concepts and ideas (Magnusson et al., 1999). This knowledge allows teachers to elicit and identify students' initial ideas, productively interpret student thinking, and select appropriate tasks to advance student understanding (Garriz et al., 2008; Talanquer, 2004).

Some authors have suggested that what teachers pay attention to has a great influence on the decisions they make and the actions they implement in the classroom (Russ, 2018). Russ (2018) has highlighted different approaches in the characterization of teacher attention to student thinking that consider the object of attention, the level of attention, the knowledge used in teacher attention, and the discursive practices employed in listening to students' thinking. This author has suggested that although these different approaches point to critical elements in a teacher's attention, it is also important to consider the messages that teachers implicitly send to students by what they pay attention to (i.e., what knowledge elements, ways of thinking, or practices they highlight).

The discourse moves that teachers use in working with student thinking seem to have a major influence on the level of reasoning manifested in a classroom (Michaels & O´Connor, 2015). Specific types of talk have been recognized as better at fostering construction of knowledge and scientific reasoning. For example, "accountable talk" (Wolf, Crosson, & Resnick, 2006) or "exploratory talk" (Mercer, 2004) engage students in sharing ideas based on explicit facts, making coherent relations, and generating reasonable conclusions (Michaels, O' Connor, & Resnick, 2008).

Mortimer and Scott (2003) have proposed five critical dimensions in the analysis of the interactions and meanings constructed in the classroom: communicative approach, teacher's intentions, content, interaction patterns, and teacher interventions. A teacher's communicative approach is characterized on a continuum that stretches from an interactive/dialogic approach to a non-interactive/authoritative approach. When teachers adopt a dialogic approach, they explore students' ideas and create opportunities for students to construct their understanding through dialogue. When teachers adopt an authoritative approach, they present a specific point of view that students are expected to understand and embrace.

The interaction patterns in which teachers engage in a classroom and the pedagogical interventions that they implement are guided by their pedagogical intentions (Mortimer & Scott, 2002). Through their use of spoken and written language, teachers work as mediators during the learning process creating or constraining opportunities for the development of student reasoning (Mercer, 2004; Michaels et al., 2008). Studies in this field have revealed the central role that classroom dialogue plays in shaping the learning that takes place (Dawes, 2004; Maine & Hofmann, 2016; Mercer & Howe, 2012; Michaels & O´Connor, 2015; Rojas-Drummond, Torreblanca, Pedraza, Vélez, & Guzmán, 2013). For example teachers that elicit students' ideas, engage with these ideas in meaningful ways through conversation, and adapt instruction in response to these ideas are more likely to foster the development of meaningful understandings (Thompson et al., 2013; Windschitl et al., 2012).

A teacher's pedagogical interventions may be varied and guided by diverse intentions, such as exploring students' ideas, sharing meanings, highlighting key ideas, monitoring comprehension, or gathering and anticipating meanings (Mortimer & Scott, 2002). These interventions send messages to students about the types of understandings, skills, ways of reasoning, and practices that are valued (Russ, 2018). A core goal of the present study was to investigate how a teacher's approach and interventions shaped the type of reasoning that students expressed after a chemistry lesson. The results of our analysis provide insights into the productive and constraining effects that teacher mediation has in the development different forms of reasoning in the classroom.

Research Questions

This study focused on a) the analysis of students´ written explanations after a chemistry lesson on freezing point depression seeking to characterise change in underlying ways reasoning, and b) the analysis of how a teacher's decisions and actions in the classroom shaped students' expressed reasoning. In particular, the following research questions guided our study:

- *How does student reasoning change as a result of a teaching intervention?*
- *How do a teacher's decisions and actions influence the types of reasoning that students express after a lesson?*

Methodology

Context and Participants

This research was carried out in a Chilean private-subsidized secondary school. Data was collected from two 10th grade chemistry classes taught by the same teacher with a total of 78 students (39 Female; 39 Male). The participating teacher had been involved in training and professional development programs that focused on the implementation of high-leverage teaching practices in the classroom (Grossman et al., 2009). Some of these practices included: (1) Explaining core content, (2) Eliciting and fostering student thinking, (3) Identifying common patterns in student thinking, and (4) Developing appropriate pedagogical responses. Although the participating teacher had only two years of teaching experience, she was already involved in mentoring preservice teachers who visited her classroom. Data were collected as part of a lesson on the topic of colligative properties, in particular freezing point depression. The objective of this lesson was to explain the relationship between freezing temperature and solution concentration. Proper consent was obtained from all participants in the study.

Research Instrument

The research instrument used to explore student reasoning was the same described in a previous study (Moreira et al., 2019). The probe described a hypothetical scenario and asked students to build a written explanation for why alcohol can be used as an anti-freezer in cars. The probe also asked students to create a drawing to support their explanation. The instrument was used to probe student reasoning before and after the lesson on freezing point depression designed by the participating teacher.

Data Collection

Data was collected from the two 10th grade chemistry classes taught by the participating teacher. Both classes were video-recorded and student written work associated with the research probe was collected. The teacher planned and implemented the observed lesson on her own, without any researcher intervention. The only request was for her to apply the research instrument at the beginning and end of the lesson. The lesson sequence is summarized in figure 1. The initial 10 minutes and the final 10 minutes of the class were used for the students to individually complete the research instrument. The remaining 25 minutes were dedicated to the lesson. During this time, the teacher first started a conversation about the freezing of pure substances using water as an example. Then, she engaged students in thinking about what may happen when a solute like salt is added to water. Different resources were used to support the lesson, such as images and video. The teacher interacted with students on a regular basis by asking different questions and reacting to students' responses. The teacher repeated the same sequence of events in the two observed classes. At the end of these classes, a total of 148 written explanations to the research probe were collected (74 initial explanations and 74 final explanations).

Data analysis

Written explanations and classroom interactions were analysed using a constant comparison method (Creswell, 2013; Miles & Huberman, 1994). To answer the research question, the analysis was conducted at two different levels. First, we characterised students´ reasoning in post-lesson written explanations and the reasoning that underlay teacher´s explanation built during the lesson. Second, we analysed how different reasoning components manifested during the lesson in relation with the teacher's interventions. In both cases, the analysis was carried out by the first two authors of this study on a representative data sample and individual codes were then compared and discussed. Disagreements were resolved through various rounds of discussion. The final schemes were then applied by the first author of this paper to analyse the entire data set.

Our analysis of reasoning in written work and in the classroom relied on the framework developed in our previous work (Moreira et al., 2019). This framework can be used to characterize different elements in an explanation:

a) *Entities (E):* Material components of the system. They may include macroscopic (e.g., substances) or submicroscopic (e.g., particles) components.
b) *Properties (P):* Characteristics of the entities that are relevant in building the explanation. They may be general or

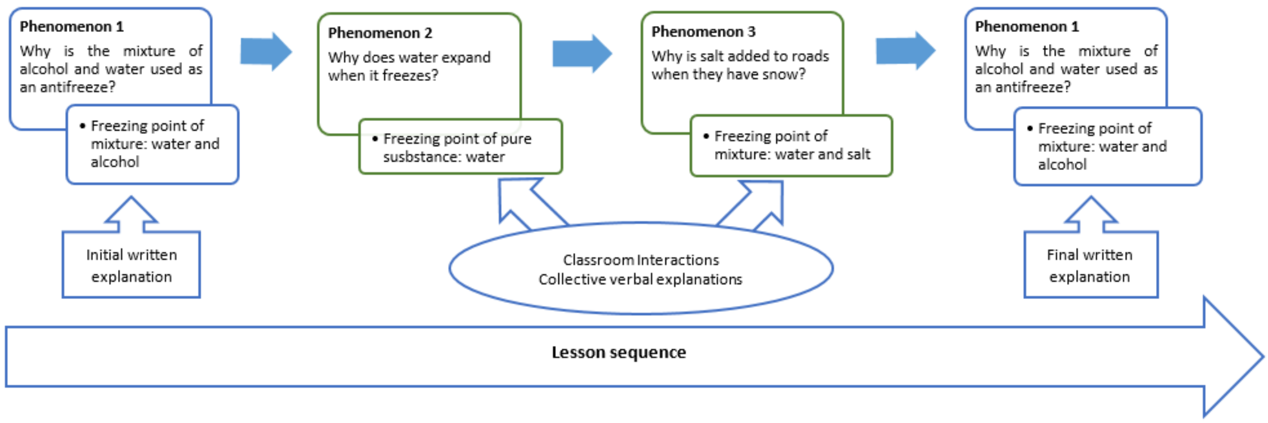


Fig. 1: Sequence of events for the lesson observed in both chemistry classes

specific. Some examples include freezing point and mass. The analysis identifies the entity associated with the cited property and the type of property that is invoked.

c) *Activities (A):* Actions/interactions cited as causing changes to entities and/or to the whole system. These activities establish explicit cause-effect relationships. The analysis identified what entity is involved in the action or interaction, and, the type of activities (there may be more than one) invoked in the explanation.

d) *Organization (O):* This category refers to the spatial-temporal location of the entities during a determined activity and its causal connection to the properties or behaviour of the system.

e) *Representations (R):* This category refers to the extent to which the drawing provides additional insights into student reasoning. Drawings were used in our analysis to identify other explanatory components not present in the written explanations, such as entities or organization.

The types of elements manifested in each of the collected explanation, and the relationship between them, was made explicit using reasoning diagrams such as that illustrated in figure 2. In these diagrams, different coloured shapes are used to identify different types of reasoning elements, and blue arrows represent causal connections.

In the second part of our analysis, we applied the framework developed by Mortimer and Scott (2002) to characterise classroom talk. In particular, we used their characterization of teachers' interventions to describe the teacher's decisions and actions when constructing explanations about freezing point depression in the classroom. Three of the categories of analysis involved exploring students´ ideas and working with meanings. These categories were *shaping meanings*, *selecting meanings, and marking key meanings*. The other categories were: *sharing meanings,* when the teacher made meanings available to all students in the class; and m*onitoring student understanding,* when the teacher verified what meanings students attribute in specific situations. Here we present specific descriptions of the teacher´s actions associated with each of these categories:

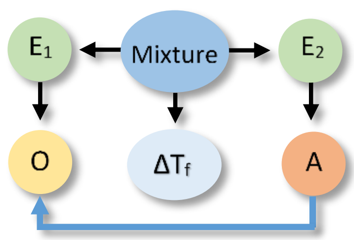


Fig. 2. Example of reasoning diagram. In this case, the explanation attributes the phenomenon of freezing point depression ΔT_f in a water (entity E_1) – alcohol (entity E_2) mixture to an activity (A) of E_2 that affects the organization of E_1.

a) *Shaping meanings*: The teacher introduces a new term, paraphrases a student's response, or shows the difference between two meanings.

b) *Selecting meanings*: The teacher considers or ignores a student's response.

c) *Marking key meanings*: The teacher repeats a statement; asks the students to repeat a statement; engages in an interrogation (I)- response (R) – evaluation (E) sequence with a student to confirm an idea; uses a particular tone of voice to highlight certain parts of a statement.

d) *Sharing meanings*: the teacher repeats the idea of a student to the whole class; asks a student to repeat a statement to the class; shares results of different groups with the class; asks students to organize ideas or experimental data to report to the entire class.

e) *Monitoring student understanding*: the teacher asks a student to explain better an idea; asks students to write their explanations; checks whether there is a consensus about certain meanings.

Main Findings

The results of our investigation have been organized into two sections. In the first section, we characterize changes the participating students' reasoning as expressed in their post-lesson written explanations. In the second section, we analyze the types of interventions made by the teacher during the lesson and how they shaped the type of reasoning that was promoted in the classroom. Qualitative data presented in the form of students' written explanations and excerpts from classroom interactions were translated from Spanish to English by a speaker fluent in both languages. Nuances in the original text and communications may have been lost in the translation.

Expressed reasoning in post-lesson student explanations

In our original study (Moreira, Marzabal and Talanquer, 2019), the analysis of the pre-lesson explanations of freezing point depression led us to the identification of four major levels of sophistication in student reasoning: Level 1 (Descriptive) included responses that were descriptive in nature and limited to restating the phenomenon in different words. Explanations in Level 2 (Relational) relied on simple associations between properties of the main entities in the system. In Level 3 (Simple Causal), explanations were based on the activities of one or more of the system's entities, while explanations in Level 4 (Emerging Mechanistic) referred to an organisation of entities and activities in space and time to make sense of the phenomenon. These same levels were used to categorize post-lesson explanations and our results are summarized in Figure 3. This figure compares the percentage of explanations classified at each level in the pre-lesson and post-lesson stages in the two observed classes. Results for the two different classes taught by the teacher have been combined in this figure as students were exposed to essentially the same lesson.

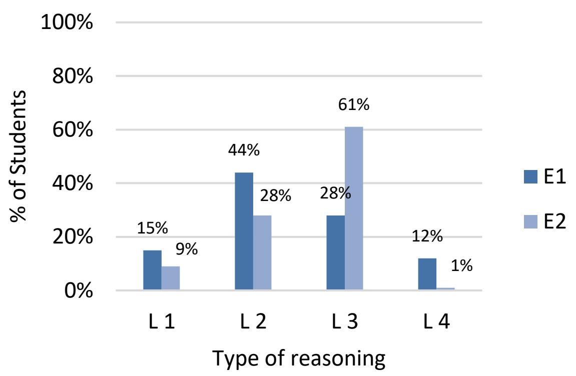


Fig. 3: Percentage of written explanations at each level of reasoning in the pre-lesson (E1) and post-lesson (E2) stages (N = 74). L1-Descriptive, L2-Relational, L3 Simple Causal, L4- Emerging Mechanistic.

Analysis of the data in figure 3 reveals a shift in the level of students' explanation towards Level 3 (simple causal). The percentage of students who expressed simple causal reasoning increased from 28% to 61%, while that of students expressing other levels of reasoning decreased, from 15% to 9% for descriptive reasoning (L1), 44% to 28% for relational reasoning (L2), and from 12% to 1% for emerging mechanistic reasoning (L4). Looking at changes in individual explanations, we determined the percentages of students that remained in the same level of reasoning or transitioned to a different level after the lesson. These results are summarized in table 1. A significant fraction of students initially at levels 1 (60%), 2 (35%), and 3 (67%) remained at those same levels. Nevertheless, a significant number of participants initially at levels 1 and 2 transitioned to higher levels of reasoning. Some students initially at level 2 moved to level 3 (59%) and only one of these students transitioned from level 2 to level 4 (3%). All participants initially al level 4 (emerging mechanistic) transitioned to level 3 (simple causal), and one third of students initially at level 3 ended expressing reasoning at level 2 (relational).

Although a large percentage of students in our sample (46%) expressed the same level of reasoning before and after the lesson, the content of their explanations changed. Table 2 shows a representative example in which a student's expressed reasoning remained at level 3, but the pre- and post-lesson explanations included different reasoning components. In this case, the initial explanation invoked a property of alcohol particles that caused them through an activity (hindering) to alter the properties of water. In the post-lesson explanation, references to properties disappeared and the phenomenon was explained by simply referring to the effect of an activity (hindering) of the alcohol particles on an activity (ordering) of water molecules.

Table 1. Percentages of students that remained in the same level of reasoning (e.g., 1-1, 2-2) or transitioned to a different level (e.g., from Level 1 to 2 → 1-2, from level 4 to 4 → 4-3) after the lesson.

Nivel 1	%	Nivel 2	%	Nivel 3	%	Nivel 4	%
1-1	**60**	2-1	3	3-1	0	4-1	0
1-2	20	2-2	**35**	3-2	33	4-2	0
1-3	20	2-3	59	3-3	**67**	4-3	100
1-4	0	2-4	3	3-4	0	4-4	**0**

The transition from levels of reasoning 2 (relational) to 3 (simple causal) was characterized by the introduction of "activity" components in students' expressed reasoning. In several of these cases, references to the properties of entities invoked in the initial explanations disappeared and causality was only linked to activities in which the entities engaged. This is illustrated in the example included in table 3 where the student initially referred to the purity of one substance and the freezing point of the other, but only invoked the hindering effect of the alcohol on the ordering of water particles in the post-lesson explanation.

Post-lesson explanations from students who transitioned down from level 4 (emerging mechanistic) to level 3 were also often characterized by references to an activity of an entity affecting an activity of the other entity, in contrast to references to the properties and organization of the components in the initial explanations. An example of this type of transition is illustrated in table 4.

Table 2: Example of no transition 3-3

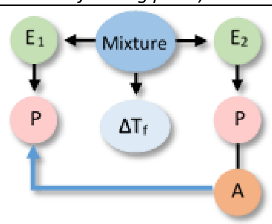
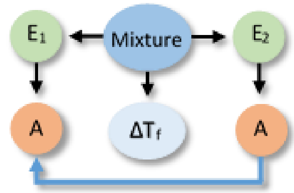
Initial written explanation	Final written explanation
May be water and alcohol act as anti-freezer because of the properties of alcohol (which are different from water's). May be the alcohol cannot freeze (hinders freezing when mixing with water). May be alcohol molecules hinder the freezing of water (lower freezing point)	*The alcohol prevents water particles from ordering, causing the freezing point to decrease Order = freezing*
	

Table 3: Example of transition 2-3

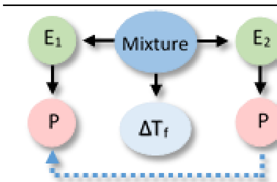
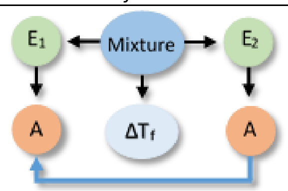
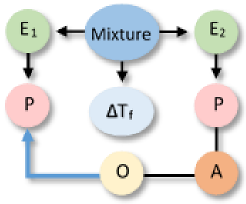
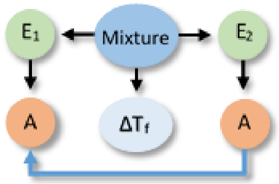
Initial written explanation	Final written explanation
Water does not freeze when adding alcohol because water goes from being a pure substance to being a solution (mixture). This causes a delay in water's freezing process because the alcohol has a different freezing point.	*In order for a solution to freeze, it needs to order its molecules. Thus, a solution takes longer to freeze than the pure solvent because when having more than one component, this component impedes a faster organization and that is why it takes longer to freeze*
	

Table 4: Example of transition 4-3

Initial written explanation	Final written explanation
I believe that the alcohol surrounds the water molecules, preventing that temperature from affecting the water. I believe also that the alcohol has a much higher freezing points than water and because it surrounds the water, it is difficult for the cold to get to the freezing point.	*The alcohol prevents the ordering of water particles, because being ordered is the same as being frozen.*





The analysis of the pre- and post-lesson explanations generated by all participants revealed a convergence towards a particular type of simple causal explanation in which the action of one of the entities (the alcohol) were responsible for the phenomenon (freezing point depression), without discussion of the properties of the entities involved or their spatio-temporal organization. There was also a reduction in the range of activities invoked by students in their explanations. Initial written explanations at levels 3 and 4 referred to activities such as hindering ordering (33%), moving (21%), reacting (21%), and repelling (12%). After instruction, however, the most common activities simultaneously invoked by students were "hindering" and " ordering" (98%). This is seen in the examples included in tables 1 through 4.

Agency in students´ written explanations

As part of our analysis, we also looked at changes in the nature of the agency invoked in students´ written explanations. The types and frequency of agency identified in pre- and post-lesson explanations are summarized in table 5. Here we can also see a convergent shift towards the alcohol acting as a barrier to or as a retardant of the freezing process. Specific examples of how students referred to different types of agency in their pre- and post-lesson explanations are presented in table 6. In the case of student 47 the alcohol passes from serving as a temperature insulator to acting as a barrier for the ordering of water molecules. For student 23, the alcohol passed from being a source of energy to be a barrier for ordering, while student 18 initially thought of the alcohol as a barrier to freezing and then characterized alcohol as a retardant.

Table 5: Agency in written explanations

	Type of agency	Pre-lesson explanation	Pot-lesson explanation
a)	Alcohol as a barrier or insulator	20%	53%
b)	Alcohol as a source of energy	13%	0%
c)	Alcohol as freezing retardant	12%	8%
d)	Alcohol as an agent that changes water	5%	4%
e)	Alcohol as a barrier or insulator AND Alcohol as freezing retardant	0	11%
f)	No agency	50%	26%

Table 6: Example of changes in agency in students´ written explanations

Student	Pre-lesson explanation	Post-lesson explanation
47	Alcohol works as a temperature insulator for water (Agency: a).	Well, what happens at the molecular level is that the solute prevents water molecules from grouping and ordering to get frozen (Agency: a).
23	They act as anti-freezer because the components in the alcohol cause the temperature of water to raise and thus it does not freeze (Agency: b).	Because the alcohol particles don't let the wáter particles to get ordered and thus it doesn't freeze (Agency: a).
18	Because when combining alcohol with water, it causes the alcohol to become a barrier that prevents water from freezing because it prevents temperature from affecting the water in the engine (Agency: a).	Water doesn't freeze because the alcohol hinders wáter particles from ordering fast and thus it needs a larger temperatura change to freeze (Agency: e).

Explanation built during the lesson

One could expect students' post-lesson explanations to be influenced by the discourse and events that took place during the lesson. Thus, the explanation that the participating teacher built with her students was also characterized using a reasoning diagram in our analysis. This diagram is presented in figure 4, together with a transcript of a moment during the lesson in which the teacher summarized the core idea she wanted the students to understand. In this explanation, we identified references to two entities (water and alcohol molecules) and to an activity (hindering) of one entity (alcohol molecules) that affected an activity (ordering) of the other

"If we think, for a substance to freeze it has to get ordered. If I am alone, happy, (points to figure representing pure water at the molecular level) and the temperature begins to decrease, the molecules will begin to order, right? If I have a solution and the temperature begins to decrease, like Laura said, it will take more for the water molecules to get ordered, right? The solute is interfering there. Then, they can get ordered, but it will take a longer time."

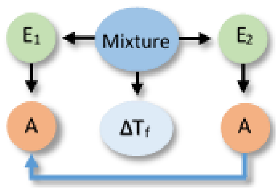


Fig. 4: Teacher´s explanation and the corresponding reasoning diagram.

entity (water molecules). In this case, there is no reference to any properties of the entities involved or to their specific spatio-temporal organization. In terms of agency, the alcohol is conceived as an entity that interferes with the ordering of water molecules, delaying freezing (alternative conception). Not surprisingly, this explanation shares many similarities with the ones generated by students after the lesson. In the following paragraphs, we analyse how this "convergence" was achieved by the teacher through different pedagogical interventions. We use excerpts from one of the lessons to illustrate the nature of the teacher's interventions observed in both classes.

As summarized in figure 1, the teacher guided the lesson using the same plan in both class sections. Thus, we present examples from only one of the lessons as they are representative of her interventions and actions in both cases. She began the lesson by directing students to analyse differences between water in the solid and liquid states at the molecular level. She presented a video that dynamically represented the freezing of water at the particulate level, and then posed the question: "*What is the difference when we have solid water versus liquid water? What is the difference at the molecular level? Katie?*" She directed the question to a specific student (pseudonym, *Katie*), but interacted with several students as she explored their thinking as shown in the following excerpt:

Teacher*: What is the difference when we have solid water versus liquid water? What is the difference at the molecular level? Katie?*
Katie*: That the solid ones are much closer*
Teacher*: Are we all in agreement with that? What happens if I put a bottle full with water in the freezer? What do you think?*
Student*: It explodes*
Teacher*: Why does it explode?*
Students*: (¿?)*
Teacher*: It is like a beer bottle which has a high percentage of water. If one freezes the bottle full with water, or the beer bottle, it bursts. Why does it burst?*
Student: *With the beer bottle or the water bottle, one has to make a sudden movement, like hitting the bottle for it to explode because if one just does it normally….*
Teacher*: Please, raise your hand to participate. Carlos?*
Carlos*: I think the gas explodes*
Teacher*: Louder, Carlos. Gas? If the water is normal? Yeah, beer has gas, but if it is tap water? Not carbonated.*
Katie*: The same, because the particles are like looser at the moment when they squish together*
Teacher*: What Katie says is what happens with all liquids. At the moment they freeze, their particles get closer together, except with water. Then, what is going to happen in the case of water? The water expands… You could do the experiment. If we make ice in the freezer and put water up to the rim, when we take it out, the ice surpasses the rim. Have you noticed it? And if you just fill half with water, then the ice fills the container. Thus. are the water molecules closer?*
Students: *No.*
Teacher: *No, right? In fact, the molecules expand. This is, they get farther apart not closer together*

In this conversation, the teacher intended for the students to recognize that water expands (its molecules get farther apart) when freezing by asking them to think about what happens when a water bottle is put inside a freezer. In her interactions, the teacher elicits student reasoning (the bottle explodes), monitors student understanding (why does it explode?), redirects student thinking (what if we have pure water with no gas?), selects meanings (what Katie says is…) and uses these ideas to present a targeted explanation (molecules of water get farther apart when water freezes). By the end of this dialogue, the teacher has marked several meanings, such as the special properties of water upon freezing (expansion versus contraction) and the general change in the distribution of water molecules that occurs during the process. The targeted phenomenon (water expands upon freezing) is explained in terms of the spatial separation of molecular entities.

After this interaction, the teacher created another opportunity to explore students' ideas by posing the following question:

Teacher: *In regards to molecular ordering, where do you think are molecules more ordered, when they are in the solid state or in the liquid state? Let's talk about water, when they are in the solid state or when they are in the liquid state? Raising your hand. Laura (pointing to a student).*

In posing this question, the teacher seemed to want to direct her students' attention to an additional aspect of molecular organization (degree of ordering). Nevertheless, the interaction with students takes the conversation in a different direction:

Laura*: Solid*
Teacher: *¿Why?*
Student*: Because they are tighter together*
Teacher: *Are they tighter? In the solid state? Why? Why would they be squished together in the solid state? Marisa? Antonio?*
Antonio*: Because there is less energy*
Teacher*: Excellent! Less kinetic energy, right? Everybody knows it. That does not change in water. Just because molecules are farther apart, that does not change the fact that they have less kinetic energy. Then, let's see this (she projects an image from the video), what is the difference at the molecular level?*

In this dialogue, students reverted back to the idea that molecules in the solid state are closer to each other than in the liquid state. When the teacher pressed for further explanation (why are they closer?), a student introduced a new idea based on the lesser amount of energy in the system. The teacher marked the idea by revoicing, shaping, and sharing it with the class, but actually did not pursue it. Instead, she presented a static molecular image of water in the liquid and solid states to redirect students' attention to molecular organization (ordering of water molecules):

> ***Teacher****: Pay attention to this, water molecules in the solid state. Internet images of ice crystals are different. When water freezes, it forms highly ordered structures. When the water molecules begin to order, they take more space. Look at the chaos in the liquid state, right? The order that we have in the solid state, do you see it? Right? I just wanted you to see this image. Water in the solid state has a highly ordered structure versus water in the liquid state*

In this explanation, the teacher highlights the ordering activity of water molecules during the freezing process. To monitor students' understanding and recapitulate meanings, she then asked:

> ***Teacher:*** *Thus, what has to happen at the molecular level for a substance to freeze? Raising your hands, Jorge.*
> ***Jorge****: It has to get ordered*
> ***Teacher:*** *Molecules have to get ordered, right? Katie.*
> ***Katie:*** *Mrs., and why it only happens in water?*
> ***Teacher:*** *This happens to all substances*
> ***Student:*** *No, but the fact that it expands*
> ***Teacher:*** *Because of hydrogen bonding. But that we will discuss in another moment, because it does not have to do much with this. Because of hydrogen bonding, but it would require us to go into much detail. It has to do with the hydrogen bonds that water forms. Carlos?*
> ***Carlos:*** *In that case, water would have to be a polar substance?*
> ***Teacher:*** *Yes. Let's go back to our image.*

In this excerpt, we can see the teacher selecting the meanings she wanted to pursue and discarding others. She marked the idea of ordering of water molecules during the freezing process but a student questioned why water expands upon freezing. The teacher referred to a specific property of water molecules (hydrogen bonding) to justify the behavior, but indicated that going into that level of detail was unnecessary. Another student referred to polarity as specific property of water to justify the behavior, an idea that the teacher confirmed but chose not to pursue either. In general, the teacher emphasized the importance of one activity of water molecules (ordering) during her interactions with students, minimizing discussions related to specific properties of water that affected the phenomenon under consideration (water freezing).

In the next part of the lesson, the teacher asked students to consider the differences in the freezing behaviors of pure water and a solution of water with salt as illustrated in the following class excerpt:

> ***Teacher:*** *…if we have pure water and need to freeze it, and if we have water with salt and we need to freeze it too, what needs to happen for them to freeze? In which case, the pure solvent or the solution will it cost more for them to freeze? Why? The why is what matters most.*
> ***Student:*** *I believe… in the solution*
> ***Teacher:*** *It will cost more in the solution.*
> ***Student:*** *because where we have the solute it would cost more for the particles to order, because the particles are different*
> ***Teacher:*** *OK, what else? Someone agrees? Anyone thinks something different?*
> ***Student 1:*** *I think the same thing. The solute is very important because of its different components, no? yes?*
> ***Teacher:*** *You said you thought the same thing, but?*
> ***Student 1:*** *ehh, what do you call it? Because it has other components besides pure water. Maybe because how the solute is composed, it may cost more to freeze it.*

In this interaction, the teacher explored students' ideas without selecting or marking any of them. There were no attempts to monitor student understanding either. In general, students assumed that the alcohol had a property that would affect the freezing of water but without providing any details on what that property may be or about the mechanism through which the effect would occur. The teacher then just moved to provide an explanation:

> ***Teacher****: … If we think, for a substance to freeze it has to get ordered. If I am alone, happy, (points to figure representing pure water at the molecular level) and the temperature begins to decrease, the molecules will begin to order, right?* ***If I have a solution and the temperature begins to decrease, like Laura said, it will take more for the water molecules to get ordered, right? The solute is interfering there. Then, they can get ordered, but it will take a longer time***

The teacher introduced the idea that the molecules of the solute (alcohol) interfered with the ordering of water molecules during freezing, causing the process to take a longer time. In the above excerpt, the teacher conflated the effect of the solute on the freezing point (depression of the freezing temperature) with a change in the time it would take for the mixture to freeze. Nevertheless, the analysis of the subsequent dialogue shows that she wanted students to recognize that the freezing temperature of the solution would be lower than that of the pure solvent:

> ***Teacher****: What needs to happen for the solution to freeze, if, let say that pure water freezes at zero Celsius? What should happen? Raúl?*
> ***Raúl****: The freezing points will have to equalize.*
> ***Teacher****: Louder!*
> ***Student****: They need to equalize…*
> ***Teacher****: Is the solution going to freeze at zero Celsius?*
> ***Students:*** *No.*
> ***Teacher:*** *At what temperature is the solution going to freeze? Katie?*
> ***Katie:*** *I believe that lower*
> ***Teacher:*** *OK. This is something we need to be careful about, because we need to lower the temperature. What will happen as we lower the temperature?*
> ***Student:*** *It will freeze faster*

> ***Teacher:*** *It freezes more, right? If I keep lowering the temperature, that favors ordering and the solution is going to freeze.*

In this excerpt, we can see that the conflation of ideas related to changes in freezing time versus changes in freezing temperature due to the presence of the solute was also present in students' ideas and was not resolved by the teacher. When a student implied that the solution would freeze faster at lower temperatures, the teacher shaped the meaning to indicate that lower temperatures would favor more order in the system. Then, she moved to discuss how the concentration of the solute would affect the freezing point as shown in this excerpt:

> ***Teacher***: *And if I have a salt solution and I add twenty salt teaspoons and then other with fifty teaspoons, which one is going to freeze at a lower temperature?*
> ***Students***: *the one with more teaspoons*
> ***Teacher****: Why?*
> ***Student****: Because it has a larger amount of solute*
> ***Teacher****: And? Then? It has a larger amount of solute? Based on what we said before, what does it need? At the molecular level, what needs to happen?*
> ***Student****: that because the molecules get disordered, then like the salt needs to get to a lower point for all the molecules to get ordered*
> ***Teacher:*** *That's it, OK? That's the full answer, remember.*

Through this dialogue and the rest of the lesson, the teacher emphasized that the solute affected the ordering of water molecules, "delaying" the freezing process. She highlighted the idea that this effect did not depend on the nature of the solute but on its concentration, without providing an explanation for this behavior. She consistently referred to the activities of the solute (hindering) and the solvent (ordering) during freezing, but never discussed the actual molecular mechanism responsible for the effect.

Discussion

Our investigation revealed significant shifts in the types of explanations generated by participating students after a lesson on freezing point depression. Although a large percentage of students expressed the same type of reasoning in their pre- and post-lesson explanations, there was also a significant number of students who transitioned towards simple causal reasoning in which explanations of the phenomenon were based on the activities of one or more of the system's entities. These types of transitions occurred in both directions, from more simplistic forms of reasoning (i.e., descriptive and relational) to simple causal and from more sophisticated types of reasoning (e.g., emerging mechanistic) to simple causal. Other types of transitions between reasoning levels were observed in our study, but they were less common. The diversity of types of causal agency commonly invoked was also reduced between the pre- and post-lesson responses, favoring explanations in which one of the entities (the alcohol) acted as a barrier or retardant in the freezing process of the other entity (water).

Our analysis of teacher-student interactions during the observed lesson suggests that the teacher's mediation played a central role in the shift towards simple causal reasoning that was observed. Through her interactions with students, the teacher built an explanation focused on one activity of the solute (hindering) acting on one activity of the solvent (ordering), without specific reference to the mechanism by which interactions between the two entities occurred. The teacher also deemphasized the effect that specific properties of the two components had on the phenomenon to be explained (freezing point depression). No references to spatio-temporal organization of the entities in the system were made either. Thus, it may not be surprising that many of the post-lesson explanations generated by the students aligned with the type of reasoning emphasized during the lesson. Even in those cases in which transition to a different type of reasoning was not observed, the content of the explanations included reasoning components introduced and discussed during the lesson.

In the two classes observed, the teacher used different pedagogical interventions to elicit students' ideas, select, mark, shape, and share meanings, and monitor student understanding. Through these interventions, the teacher communicated what concepts and ideas were relevant in the construction of the explanation, and which ones were not appropriate or necessary for understanding the phenomenon. Although the teacher often acknowledged the different ideas expressed by her students, she did not pursue them as part of the classroom conversations and often reshaped them to fit her own narrative. From this perspective, the observed classroom talk could not be considered as exploratory or accountable talk (Wolf, Crosson and Resnick, 2006) as most of the of the key ideas were introduced, selected, or reshaped by the teacher.

The teacher engaged students in the construction of a rather simple causal explanation of freezing point depression. This explanation had elements of "centralized" causality in its reference to the actions of an active entity (the alcohol) that affected the behavior of a more passive entity (the water) (Grotzer, 2003; Resnick, 1994; Talanquer, 2010). No references to the dynamic nature of the freezing and processes were made, and there was no consideration of how the presence of the solute affected the probability of these dynamic events. This outcome is consistent with studies about the characteristics of first-year prospective teachers' explanation of this topic (Çokadar, 2009).

Implications

Our analysis highlights the central roles that a teacher's knowledge, intentions, and pedagogical interventions have on her students' expressed reasoning at the end of a lesson. Classroom talk allows students to recognize important ideas and reach collective understandings through interaction (Mercer, 2004; Jeong and Chi, 2007), but a teacher's mediation greatly influences the learning outcomes. In our case, the ways in which the teacher understood or decided to talk about freezing point depression in the two observed classes reshaped her students' expressed reasoning, advancing their ideas in some cases but also constraining their thinking in others. In particular, emerging mechanistic forms of explanation essentially disappeared as a result of the intervention and simple "centralized" causal ways of thinking became dominant.

The participating teacher in our study frequently elicited her students' ideas and sought to guide their thinking through questioning. She engaged in several high-leverage teaching practices (Grossman et al., 2009), but her thinking and action seemed constrained by different factors. Her content knowledge and understanding of the phenomenon under consideration may have been limited, as attested by the centralized explanation that she built and the conflation of time and temperature effects on the phenomenon under discussion. It is also possible that her understanding of how to help students build meaning through dialogue may have been underdeveloped given her tendency to reshape her students' expressed thinking and to not pursue their ideas. Nevertheless, she was able to help many students advance in their reasoning.

It is unlikely that the teacher had reflected, or had given the opportunity to reflect in her professional training, about the different types of explanations that can be built about chemical phenomena (Talanquer, 2018) or about the different levels of reasoning at which such explanations can be built (Sevian and Talanquer, 2014). Teacher preparation and professional development programs rarely engage prospective or in-service teachers in the analysis of content knowledge from historical, philosophical, epistemological, and pedagogical perspectives to enrich their understanding of different ways of explaining and constructing explanations in the discipline (Freire, Talanquer and Amaral, 2019). The results of our study suggest that this type of engagement with the subject matter would help teachers approach the construction of explanations in the classroom in richer and more dialogic ways (Mortimer and Scott, 2002).

Making teachers discuss and reflect on both the different types of reasoning that students often express and the quite sophisticated ways of thinking that they are capable of manifesting with proper scaffolding, could help teachers become more responsive to their students' ideas and use those ideas in more meaningful and productive ways in the construction of classroom explanations. Our work indicates that the successful implementation of high-leverage teaching practices may require the development of teachers' PCK on two critical areas: specific ways of reasoning in the discipline and student reasoning in the domain.

Limitations

Giving the nature of our study, one should be cautious in making generalizations of our findings. We observed only one lesson taught by a single teacher in two different classrooms in a Chilean high school. The nature of the chemistry content that was taught in the observed lesson may had imposed constraints on the teachers' decisions and actions. Colligative properties are often explained using simple causal models in introductory chemistry courses, given the perceived complexities of dynamical explanations invoking competing processes with different probabilities of occurrence. Given her training and pedagogical content knowledge, it is possible that the observed teacher negotiated meanings in the classroom using a different approach when working with other topics. More observations of diverse teachers working on different topics and in diverse learning environments are needed to better understand the potentialities and challenges of teacher mediation in fostering student reasoning.

Conflicts of interest

There are no conflicts to declare.

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4 Discusión y Conclusiones

4.1 Discusión de resultados

Para facilitar la presentación y discusión de resultados de esta investigación, éstos se han agrupado en torno al cumplimiento de los objetivos específicos propuestos. En un primer apartado se dan a conocer los principales hallazgos correspondientes a la identificación de los tipos de razonamiento que subyace a las explicaciones escritas construidas por estudiantes de enseñanza media al explicar el descenso del punto de congelación de una mezcla respecto del solvente puro. Mientras que en una segunda sección de resultados se abordan aquellos que se desprenden de la caracterización de las interacciones de aula que promovieron cambios en las formas de razonamiento de los estudiantes en la clase de química.

4.1.1 Características de los tipos de razonamiento que subyacen a las explicaciones iniciales construidas por estudiantes de enseñanza media en el tópico de descenso del punto de congelación

El análisis sistemático de las producciones iniciales de los estudiantes, rebeló que 75 de las 78 correspondían a respuestas completas, es decir contenían representaciones en formato escrito y/o dibujos. De estas 75 explicaciones iniciales se identificaron 15 patrones de razonamiento los que finalmente fueron agrupados en cuatro niveles de sofisticación de razonamiento. Estos cuatro niveles fueron identificados utilizando un método de comparación constante, mediante el cual se determinó que los componentes elicitados en la explicación - entidades, propiedades, actividad y organización (Russ et al., 2008) – y sus relaciones – unidireccional/ bidireccional (Grotzer, 2003) y causal/no causal (Gilbert, 2000) – eran determinantes en el nivel de sofisticación de los razonamientos (Sevian & Talanquer, 2014) elicitados por los estudiantes en sus explicaciones.

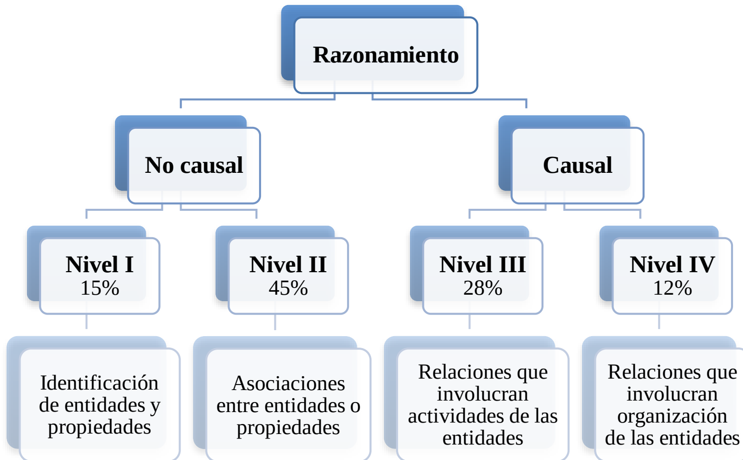

Figura 4.5. Niveles de razonamiento expresados en las explicaciones elaboradas por los estudiantes al inicio de la clase.

En la clasificación de respuestas correspondiente a un nivel no causal (véase Figura 4.5), cerca del 15% de los estudiantes expresaron un tipo de razonamiento denominado descriptivo el que se caracteriza por una re-descripción de lo observado. En la mayoría de los casos sus respuestas incluyen entidades y en menor cantidad propiedades de las entidades identificadas, no estableciendo relaciones horizontales entre los componentes del sistema. En un segundo nivel no causal se encuentran respuestas cuyo razonamiento subyacente es del tipo relacional, ubicando en este nivel un 45% de las respuestas. Este segundo nivel de sofisticación incluye la elicitación de entidades y sus propiedades, pero a diferencia del nivel I se incluyen relaciones horizontales que conectan las entidades o las propiedades de las mismas. Estas relaciones incluyen efectos del tipo unidireccionales de una entidad a otra o de una propiedad a otra, así como relaciones bidireccionales o mutuas entre las propiedades de los componentes de la mezcla. Este tipo de relaciones se han descrito en la literatura desde investigaciones sobre causalidades complejas (Grotzer, 2012; Grotzer, 2003). No obstante, la identificación de estas conexiones a nivel no causal representa un aporte al estudio sobre la construcción progresiva de relaciones causales.

En las respuestas que manifiestan un nivel de razonamiento causal se logran distinguir dos niveles de sofisticación del razonamiento, lo que apunta a la distinción entre razonamientos causal simple y mecanístico propuestos en la literatura (Machamer et al., 2000; Perkins & Grotzer, 2005; Russ et al., 2008). El primero de ellos, nivel III, en el cual se sitúa a un 28% de las respuestas, corresponde a relaciones causales simples cuyo componente clave es la incorporación de actividades de uno o ambos componentes del sistema. Estas actividades involucran una acción directa sobre una entidad, propiedad o actividad de la misma o relaciones de causalidad mutua o bidireccional entre actividades de ambas entidades. Este tipo de casos de causalidad bidireccional en algunos ocasiones está asociado a que los estudiantes atribuyen propiedades aditivas a la mezcla, resultado reportado en estudios sobre explicaciones de los estudiantes en el tópico de propiedades coligativas (Talanquer, 2010a). El cuarto nivel corresponde a uno denominado mecanístico emergente, siendo la principal característica que la explicación se basa en la organización espacio-temporal de las entidades involucradas en una determinada actividad. En este nivel un 12% de los estudiantes expresan relaciones causales unidireccionales en las cuales la organización de las entidades de uno de los componentes del sistema influye en las propiedades o actividades de otro de los componentes de la mezcla (Grotzer, 2003).

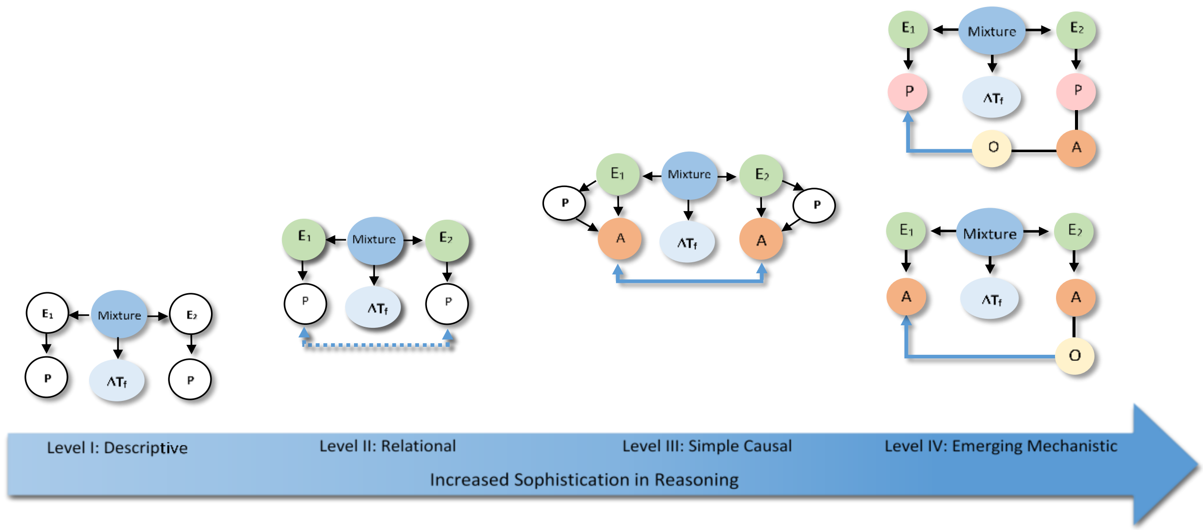

Figura 4.6. Diagramas de razonamiento representativos para cada uno de los 4 niveles de sofisticación identificados en el estudio. Diferentes colores son utilizados para representar los componentes de la explicación. La línea azul punteada en el nivel II es usada para representar relaciones no causales mientras que las líneas continuas azules representan relaciones causales entre los componentes. Los círculos en blanco y negro representan elementos que pueden o no estar presentes en cada nivel

La distribución creciente en sofisticación del razonamiento se muestra en la Figura 4.6, donde se presentan los principales patrones de razonamiento en cada uno de los niveles identificados en la muestra. Esta distribución se basa en los componentes del razonamiento elicitados y las conexiones causales y no causales entre estos componentes.

La identificación de estos cuatro niveles permitió distinguir entonces desempeños en planos causales y no causales (véase Figura 4.5). Estos hallazgos aportan evidencia sobre cómo frente a una determinada pregunta y contexto los estudiantes pueden tener un amplio rango de respuestas (Weinrich & Talanquer, 2015). Además de evidenciar distintos tipos de explicaciones de los estudiantes que pueden estar asociadas a la funcionalidad de las mismas (Gilbert et al., 2000), teniendo así desempeños causales y no causales frente a esta tarea.

Además de la identificación y caracterización de los cuatro niveles de sofisticación del razonamiento que subyace a las explicaciones de los estudiantes participantes, el análisis de las relaciones unidireccionales permitió identificar patrones de agencialidad en sus respuestas. En un 50% de las explicaciones los estudiantes establecen relaciones en las cuales el alcohol se presenta como una entidad responsable del cambio, es decir como agente activo en la solución. Esta tendencia se presenta de manera transversal en los niveles II, III y IV. Aspectos relacionados a construcción de relaciones de causalidad simple que involucran un agente causal han sido reportadas en la literatura (Grotzer, 2012). Las principales agencialidades identificadas son descritas a continuación.

- Alcohol como barrera o aislante (20%): este tipo de atribución fue observada en los niveles II, III y IV. En el nivel II generalmente se relaciona al alcohol como aislante mientras que en niveles III y IV se hace referencia al alcohol como una barrera.
- Alcohol como fuente de energía (13%): en esta forma de agencialidad se localizan explicaciones de los niveles II y III, donde principalmente los estudiantes hacen referencia al movimiento de las partículas de alcohol como responsables del cambio.
- Alcohol como retardante del punto de congelación (12%): En este tipo de agencialidad los estudiantes tienden a relacionar el descenso del punto de congelación con un factor tiempo en lugar de asociarlo a temperatura. Este tipo de explicaciones son observadas en los niveles II y IV.
- Alcohol como un agente de cambio en la composición del agua (5%): un menor número de estudiantes asociaron la presencia del alcohol en la mezcla como un agente que genera cambios en la forma o composición del agua. Estas explicaciones se localizan en niveles II y III.

Agencialidad vinculada al alcohol como agente retardante ha sido identificada en explicaciones de futuros docentes en su primer año de formación (Çokadar, 2009), por lo que estos hallazgos dan cuenta de la persistencia de estas formas de razonar en el estudiantado.

4.1.2 Construcción de explicaciones mediadas por las intervenciones docentes y su efecto en el razonamiento de los y las estudiantes

Con el objetivo de analizar las producciones construidas por los estudiantes al finalizar la clase observada se aplicó la estrategia de análisis diseñada para la primera etapa de la investigación, cuyos resultados se muestran en la Figura 4.7.

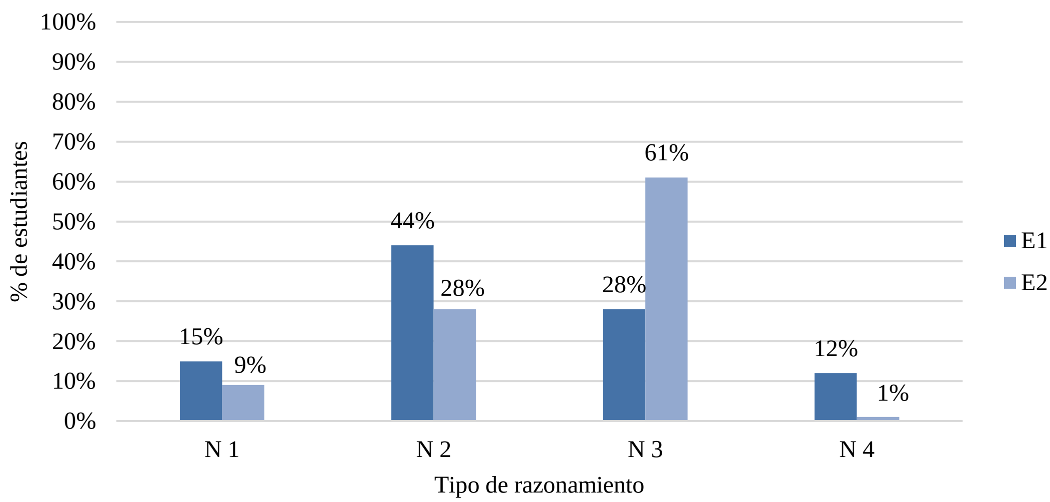

Figura 4.7. Desempeño de los estudiantes en las explicaciones escritas al inicio y al final de la sesión en función de los cuatro niveles de sofisticación de razonamiento.

En la Figura 4.7, se observa un aumento en el porcentaje de estudiantes que en la respuesta final elaboran una explicación con base en un razonamiento causal. No obstante, se presenta una disminución del razonamiento mecanístico emergente. Esto podría ser un indicio de que comienzan a construir explicaciones en base a un razonamiento coherente con la tarea planteada, debido a que estudios plantean a que no necesariamente todas las tareas demandan complejas formas de razonar (Russ et al., 2008). Así como el tipo de pregunta que antecede a la explicación determina el tipo de respuesta de los estudiantes (Gilbert et al., 2000).

La movilización del razonamiento expresado por los estudiantes al inicio y al final de la clase se muestra en la Tabla 4.8 donde se presentan las probabilidades de transición entre niveles para los 74 estudiantes que desarrollaron cada una de las actividades. De acuerdo con el análisis de las explicaciones escritas la probabilidad de que estudiantes que se encontraban en un nivel 4 (mecanístico emergente) mantengan este tipo de razonamiento es de un 0%, mientras que se presenta una probabilidad de un 100% de que los estudiantes situados en nivel 4 al inicio de la clase, se movilicen hacia un razonamiento simple causal al elaborar su explicación 2. Por otra parte, un 67% de los estudiantes situados al inicio en un nivel tres mantiene esta forma de razonamiento al construir su explicación final. Estos movimientos en las formas de razonamiento que subyacen a las explicaciones elaboradas al inicio y al final de la clase, llevaron la atención a los procesos que ocurren durante las interacciones de aula que buscaban explicar el fenómeno planteado, con el objetivo de comprender de qué manera se produjeron las movilizaciones en el razonamiento de los estudiantes entre el inicio y el final de la sesión.

Entre los principales hallazgos del análisis de las conversaciones de aula se identificaron tres fenómenos diferentes planteados en la clase, diferentes tipos intervenciones docentes y la activación de diversos componentes del razonamiento. Evidenciando además cambios en las agencialidades invocadas por los estudiantes, donde la presencia de agencialidad aumenta de un 50% a un 74% en las explicaciones finales. Siendo una de las más empleadas por los estudiantes aquella que considera el alcohol como barrera (53%). Esto se explica por el aumento de conexiones unidireccionales entre los componentes del razonamiento, los que coinciden con la explicación presentada por la docente.

Tabla 4.8. Probabilidad de transición entre niveles de razonamiento de las respuestas escritas construidas por los estudiantes al inicio y al final de la clase observada. Donde los números bajo cada columna de nivel identifica las transiciones entre niveles como, por ejemplo: 1-2 indica la probabilidad de transferencia entre el nivel 1 a nivel 2

Nivel 1	%	Nivel 2	%	Nivel 3	%	Nivel 4	%
1-1	**60**	2-1	3	3-1	0	4-1	0
1-2	20	2-2	**35**	3-2	33	4-2	0
1-3	20	2-3	59	3-3	**67**	4-3	100
1-4	0	2-4	3	3-4	0	4-4	**0**

El análisis de las interacciones de aula sugiere que la mediación docente desempeñó un papel central en la transición hacia un razonamiento causal simple. A través de sus intervenciones, la maestra construyó una explicación centrada en una actividad del soluto (obstaculización/interferencia) que actúa sobre una actividad del solvente (ordenamiento). A pesar de movilizar el razonamiento de los estudiantes hacia niveles de causalidad, la explicación que se buscaba promover no hacía referencia al mecanismo por el cual ocurrieron las interacciones entre las dos entidades de la mezcla. Por lo tanto, no es sorprendente que un 100% las explicaciones mecanísticas presentes al inicio de la clase disminuyeran en complejidad.

La aproximación hacia el reconocimiento de una única actividad en la explicación final respecto de la explicación inicial de los estudiantes (ver Tabla 4.9), puede considerarse como una evidencia de la convergencia progresiva en las formas de razonar y construir conocimiento en el aula (Jeong & Chi, 2007). Sin embargo, la tendencia en las intervenciones docentes de trabajar en torno a una única actividad, no permite clasificar este diálogo como una "*exploratory talk"* (Wolf, Crosson y Resnick, 2006).

Tabla 4.9.   Tipos de actividades elicitadas en las explicaciones de los estudiantes

Actividad	Explicación 1	Explicación 2
Orden	33%	98%
Movimiento	21%	2%
Reacción	21%	0%
Repulsión	12%	0%
Otra	12%	0%

Estos resultados dan cuenta de que a pesar de que durante la clase fue posible promover una movilización de las formas de razonamiento hacia el uso de relaciones causales en el 60% de los estudiantes, aún es necesario trabajar en torno a formas de causalidad dinámicas (Talanquer, 2018b). Causalidades que permitan vincular relaciones mutuas o bidireccionales (Grotzer, 2012), con el consecuente uso apropiado del conocimiento disciplinar. Para ello, se requiere de procesos de construcción de explicaciones intencionados en base a las formas de razonamiento que progresivamente alcancen formas de causalidad alineadas a la tarea propuesta.

Debido a la presencia de los cuatro niveles distintos de razonamiento evidenciados en este estudio, se podría pensar en una progresión en el aprendizaje de los estudiantes. Podríamos asumir que el reconocimiento de las entidades principales de un sistema y sus correspondientes propiedades serían los primeros pasos necesarios en el proceso de aprender a explicar. La construcción de asociaciones simples entre entidades y propiedades podrían seguir en esta progresión, y luego pasar a la identificación de los vínculos causales mediados por las interacciones entre las entidades y las actividades a las que dan lugar. Y en un último paso, la identificación de organizaciones espacio-temporales facilitaría la construcción de explicaciones mediante el uso de un razonamiento mecanístico.

Sin embargo, no podemos afirmar que la progresión planteada permitiría construir explicaciones con base en el razonamiento adecuado, debido a las limitaciones de nuestro estudio. Por otra parte, nuestros hallazgos no afirman ni contradicen esta posible progresión, simplemente explicitan el rango de tipos de razonamiento expresados por los estudiantes e ilustran cómo caracterizarlos sistemáticamente.

Para trabajar en torno a una posible progresión es necesario que los y las docentes consideren diversos tipos de explicaciones (Talanquer, 2010) que pueden ayudar a comprender fenómenos en el aula. Para ello, es necesario trabajar en torno a dimensiones de su conocimiento pedagógico del contenido (Magnusson et al., 1999), tales como el conocimiento de las formas de razonamiento de sus estudiantes, estrategias instruccionales y refuerzo en aspectos disciplinares de ser necesario. Con el propósito de implementar interacciones de aula en base a modelos o representaciones del contenido adecuadas a la tarea propuesta (Shulman, 1987; Garritz, et al., 2008). Cuyos movimientos de habla eliciten, reúnan y orienten el razonamiento de sus estudiantes (Michaels y O´Connor, 2015).

4.2 Limitaciones

Teniendo en consideración la naturaleza cualitativa de la investigación desarrollada, la participación de un grupo de estudiantes guiados por la misma profesora de química y el trabajo en torno a un tópico específico en el campo de la enseñanza y aprendizaje de esta disciplina de acuerdo con el marco curricular chileno, debemos ser cuidadosos con el nivel de generalización que este estudio de caso nos proporciona (Merriam, 1998). Respecto de la caracterización del razonamiento que subyace a las explicaciones escritas, se podría pensar que en algunos casos sería necesario profundizar en las ideas expresadas por los estudiantes, por lo que acercamientos a los participantes mediante entrevistas nos permitirían recopilar mayor información sobre los tipos de razonamiento que subyacen a sus producciones. Respecto de la validación de nuestros niveles de sofisticación de razonamiento, se requieren de más estudios que fortalezcan las categorías que determinan los criterios de clasificación de las respuestas en cada uno de los niveles propuestos, para alcanzar el punto de saturación de las categorías (Hernández et al., 2010).

En relación con el rol de las intervenciones docentes en el razonamiento de los y las estudiantes es importante considerar que se observó solo una clase. La naturaleza del contenido de química que se enseñó en la lección observada puede además imponer restricciones en las decisiones y acciones de los profesores. Las propiedades colectivas a menudo se explican utilizando modelos causales simples en los cursos de química introductoria, dada la complejidad percibida de las explicaciones dinámicas que invocan procesos en competencia con diferentes probabilidades de ocurrencia. Finalmente, debido a la especificidad del conocimiento pedagógico del contenido de cada docente en cada tópico de la enseñanza de la química, es necesario realizar más observaciones de diversos profesores en diferentes temas y entornos de aprendizaje para comprender mejor las potencialidades y los desafíos de la mediación docente para promover el razonamiento causal en el estudiantado.

4.3 Conclusiones

Los resultados de esta tesis doctoral, presentados en los artículos que componen este compendio, han permitido aportar evidencia sobre los tipos de razonamiento que los estudiantes en etapa escolar utilizan para dar respuesta a la tarea de explicar fenómenos cotidianos que involucren el conocimiento químico apropiado a su nivel escolar, y de qué manera las intervenciones docentes movilizan estos razonamientos en las interacciones de aula. La estrategia de análisis propuesta permitió visibilizar estas formas de razonamiento mediante la construcción de diagramas que caracterizan el razonamiento considerando sus componentes (Russ et al., 2008), relaciones (Gilbert, 2000; Grotzer, 2003) y nivel de sofisticación (Sevian & Talanquer, 2014). La integración de estos marcos teóricos en la propuesta de análisis representa un aporte metodológico al campo de la investigación sobre razonamiento químico, presentándose como una propuesta teórica y analítica para la caracterización de este objeto de estudio.

El marco de análisis propuesto permitió la identificación de diversos tipos de razonamiento expresados por los participantes. La agrupación de estos patrones de razonamiento en función de características comunes, dio paso a la construcción de cuatro niveles de sofisticación que se plantean como una posible progresión sobre cómo las formas de razonamiento del estudiantado en etapa escolar pueden ir transitando hacia la construcción de complejas formas causales en el aula. Estos hallazgos representan una contribución teórica al campo de la investigación en educación química, la que a su vez abre desafíos sobre cómo guiar estas progresiones en el aula.

Finalmente, la identificación y caracterización de las formas de razonamiento individuales y colectivas en torno al tópico específico abordado en este estudio, junto con los niveles de sofisticación de razonamiento propuestos, pueden ser utilizados por los docentes interesados en desarrollar en sus estudiantes prácticas científicas como la explicación. Mediante la construcción de los diagramas de razonamiento los docentes pueden evaluar si el razonamiento utilizado y las conexiones establecidas entre los distintos factores son las apropiadas para la tarea propuesta. La consideración de diversas formas de explicar los fenómenos planteados en el aula permite tanto a profesores como estudiantes transitar entre distintas formas de razonamiento y causalidad, contribuyendo en el proceso de toma de decisiones pedagógicas, generando estrategias de enseñanza adecuadas al contexto y necesidades de sus estudiantes.

4.4 Proyecciones

Los hallazgos que se desprenden de esta tesis doctoral proyectan una línea de investigación que aborde las formas de razonamiento individual y colectivo que expresan los estudiantes en el proceso de aprendizaje en diversos tópicos de la química escolar. Además de ampliar el foco de estudio hacia el análisis de la mediación docente y el diseño de propuestas de enseñanza que promuevan la movilización de distintos tipos de razonamientos en el aula.

Los resultados de este estudio evidencian que, si bien hemos caracterizado las formas de razonamiento de los estudiantes en un tópico específico que aborda cambios físicos en la enseñanza y aprendizaje de la química, se hace necesario ampliar el foco de estudio hacia temáticas que involucren cambios químicos en las explicaciones del estudiantado. El análisis de estos tópicos permitiría establecer diferencias entre los componentes del razonamiento elicitados y las conexiones entre éstos que permitan identificar los diversos niveles de sofisticación del razonamiento en distintos ámbitos de la química escolar.

El estudio realizado indica que frente a una determinada tarea es posible encontrar un amplio rango de respuestas de los estudiantes las que van desde razonamientos descriptivos hacia niveles de causalidad compleja como la del tipo mecanístico emergente. El análisis de la conversación de aula mostró cómo progresivamente estas formas de razonamiento convergen en su mayoría en el uso de un tipo de actividad y cómo ello potencia el uso de un razonamiento causal simple, bajo un conjunto de intervenciones docentes movilizadas por la intención de alcanzar un determinado tipo de explicación. Si bien estos son avances relevantes en la caracterización de las formas de razonamiento que subyacen a las explicaciones científicas escolares, vemos necesario proyectar estudios que trabajen en la articulación de las formas de razonamiento con la adecuada elicitación de componentes disciplinares para construir explicaciones coherentes a la tarea y cuyos elementos disciplinares sean coherentes con las teorías y modelos científicos que explican los fenómenos en estudio.

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