22 de noviembre de 2018
Dictamen 20/18

DICTAMEN
QUE PRESENTA LA COMISIÓN DE INVESTIGACIÓN DE LA DIVISIÓN DE CIENCIAS DE LA COMUNICACIÓN Y DISEÑO.

ANTECEDENTES

I. El Consejo Divisional de Ciencias de la Comunicación y Diseño, en la sesión 08.18, celebrada el 16 de mayo de 2018, integró esta Comisión en los términos señalados en el artículo 55 de Reglamento Interno de los Órganos Colegiados Académicos.

II. El Consejo Divisional designó para esta Comisión a los siguientes integrantes:

a) Órganos personales:
- ✓ Dr. Jesús Octavio Elizondo Martínez, Jefe del Departamento de Ciencias de la Comunicación;
- ✓ Mtro. Luis Antonio Rivera Díaz, Jefe del Departamento de Teoría y Procesos del Diseño;
- ✓ Dr. Carlos Joel Rivero Moreno, Jefe del Departamento de Tecnologías de la Información.

b) Representantes propietarios:
- Personal académico:
  - ✓ Mtro. Daniel Cuitláhuac Peña Rodríguez, Departamento de Ciencias de la Comunicación;
  - ✓ Dra. Dina Rochman Beer, Departamento de Teoría y Procesos del Diseño.
  - ✓ Dr. Alfredo Piero Mateos Papis, Departamento de Tecnologías de la Información;

CONSIDERACIONES

I. La Comisión recibió, para su análisis y discusión el informe final del proyecto de investigación denominado ***"Modelo computacional para el estudio de la generación colaborativa de narrativas textuales y visuales"*** presentado por el Dr. Rafael Pérez y Pérez, aprobado en la Sesión 08.12 celebrada el 11 de julio de 2012, mediante el acuerdo DCCD.CD.09.08.12. Asimismo, fue aprobada una prórroga hasta diciembre de 2016, en la Sesión 01.16 celebrada los días 25 y 28 de enero de 2016, mediante el acuerdo DCCD.CD.11.01.16.

II. La Comisión de Investigación sesionó el día 21 de noviembre de 2018, fecha en la que concluyó su trabajo de análisis y evaluación del informe, con el presente Dictamen.

División Ciencias de la Comunicación y Diseño

Unidad Cuajimalpa
DCCD | División de Ciencias de la Comunicación y Diseño
Torre III, 5to. piso. Avenida Vasco de Quiroga 4871,
Colonia Santa Fe Cuajimalpa. Delegación Cuajimalpa de Morelos,
Tel. +52 (55) 5814-6553. C.P. 05300, México, D.F.
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III. La Comisión contó, para su análisis, con los siguientes elementos:
- Protocolo de investigación.
- Relevancia para la división.
- Congruencia global.
- Metas-Recursos.
- Evaluación general.

IV. La evaluación de los resultados de investigación se llevó a cabo de acuerdo con los *"Lineamientos para la creación de grupos de investigación y la presentación, seguimiento y evaluación de proyectos de investigación"* aprobados en la Sesión 06.16 del Consejo Divisional de Ciencias de la Comunicación y Diseño, celebrada el 6 de junio de 2016, mediante al acuerdo DCCD.CD.15.06.16

DICTAMEN

ÚNICO:

Tras evaluar el informe final del proyecto de investigación *denominado* ***"Modelo computacional para el estudio de la generación colaborativa de narrativas textuales y visuales"*** presentado por el Dr. Rafael Pérez y Pérez, la Comisión de Investigación recomienda al Consejo Divisional de Ciencias de la Comunicación y Diseño aceptarlo.

VOTOS:

Integrantes	Sentido de los votos
Dr. Jesús Octavio Elizondo Martínez	**A favor**
Mtro. Luis Antonio Rivera Díaz	**A favor**
Dr. Carlos Joel Rivero Moreno	**A favor**
Mtro. Daniel C. Peña Rodríguez	**A favor**
Dr. Alfredo Piero Mateos Papis	**A favor**
Dra. Dina Rochman Beer	**A favor**
Total de los votos	**6 votos a favor**

Coordinadora

Dra. Gloria Angélica Martínez De la Peña
Secretaria del Consejo Divisional de
Ciencias de la Comunicación y Diseño

Casa abierta al tiempo
UNIVERSIDAD AUTONOMA METROPOLITANA
Unidad Cuajimalpa
Oficina Técnica del
Consejo Divisional

División Ciencias de la Comunicación y Diseño

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Casa abierta al tiempo
UNIVERSIDAD AUTÓNOMA METROPOLITANA
Unidad Cuajimalpa

Comunidad académica comprometida con el desarrollo humano de la sociedad.

DCCD.DTI.116.18
Noviembre 8, 2018

Dr. Octavio Mercado González
Presidente del Consejo Divisional de la
División de Ciencias de la Comunicación y Diseño
Unidad Cuajimalpa
Presente

Asunto: Informe final de proyecto de investigación

Estimado Dr. Mercado:

Por este conducto le hago entrega del informe final para su cierre del Proyecto de Investigación:

"*Modelo Computacional para el Estudio de la Generación Colaborativa de Narrativas Textuales y Visuales*"

El responsable es el Dr. Rafael Pérez y Pérez, Profesor-Investigador adscrito a este Departamento, y miembro del Grupo Interdisciplinario en Creatividad Computacional, UAM Cuajimalpa.

Se anexan las carátulas de los trabajos presentados como resultado.

Se envían los documentos indicados y anexados en formato digital, vía correo electrónico.

Sin otro particular, envío a usted un cordial saludo.

Atentamente,

Casa abierta al tiempo

Dr. Carlos Joël Rivero Moreno
Jefe del Departamento de Tecnologías de la Información

Anexo: Informe final de proyecto de investigación y trabajos presentados como resultado.

c.c.p.: Dra. Gloria Angélica Martínez de la Peña – Secretaria del Consejo Divisional
Lic. Inés Andrea Zepeda Martínez – Oficina Técnica de Consejo Divisional.

CJRM

Reporte de Resultados de la Extensión del Proyecto

Modelo Computacional para el Estudio de la Generación Colaborativa de Narrativas Textuales y Visuales

La siguiente tabla muestra un comparativo entre las actividades a las que nos comprometimos a realizar durante la extensión del proyecto y las que realmente realizamos.

Actividad	Compromiso	Resultado final
Generar un artículo para revista	1	1
Generar un artículo para congreso	1	1
Organizar un evento internacional	1	2
Organizar un seminario de cierre del proyecto	1	1

Generar un artículo para revista
Durante este período se generó un artículo para revista indizada (JCR) el cual fue enviado para su evaluación en el 2016 y publicado en 2017:

Aguilar, W. & Pérez y Pérez, R. (2017). Emergence of eye–hand coordination as a creative process in an artificial developmental agent. *Adaptive Behavior*, pp. 1-26.
https://doi.org/10.1177/1059712317732116

Generar un artículo para congreso
Durante este período se generó un artículo para congreso el cual fue presentado en la ICCC16 y se incluye en las memorias del mismo:

Guerrero, I. & Pérez y Pérez, R. (2016). Knowledge structures of an automatic storyteller and their relevance for its generated stories. In Proceedings of the Seventh International Conference on Computational Creativity, Paris.
http://www.computationalcreativity.net/iccc2016/proceedings-2016/

Organizar un evento internacional
En este rubro incluimos el evento que se llevó a cabo en el 2015, el cual no fue considerado en el reporte original, así como el que se llevó a cabo en el 2016:

2015
10º Coloquio Internacional en Creatividad Computacional:
Los videojuegos y la creatividad computacional.
Invitados especiales:
Clara Fernández, Universidad de Nueva York, EEUU
Dr. Pablo Gervás, Universidad Complutense de Madrid
Dr. Michael Mateas, Universidad de California, Santa Clara, EEUU

2016
11º Coloquio Internacional en Creatividad Computacional:
La creatividad computacional y el lenguaje.
Invitados especiales:
Dra. Anna Jordanous, Universidad de Kent, Reino Unido
Dr. Paolo Rosso, Universidad Politécnica de Valencia
Dr. Juan Manuel Torres, Laboratorio de Informática de Avignon, Francia.

Organizar un seminario de cierre del proyecto
Se llevó a cabo un seminario del cierre del proyecto donde se generó un documento interno que fungió como una reflexión integradora y de cierre del proyecto realizado. Se anexa dicho documento.

De esta manera, cumplieron de manera cabal, en tiempo y forma, con los compromisos del proyecto.

Reporte de Resultados

Proyecto: Modelo Computacional para el Estudio de la Generación Colaborativa de Narrativas Textuales y Visuales

Introducción

En 2012 el Grupo Interdisciplinario en Creatividad Computacional de la UAM Cuajimalpa sometió una propuesta de proyecto de investigación de ciencia básica interdisciplinario al CONACYT. Dicho solicitud resultó favorecida con un apoyo de 2012 a 2015. Siguiendo las indicaciones de la Dirección de la DCCD, solicitamos el registro del mismo ante el Consejo Divisional. Nuestra petición ingresó en julio de 2012 y fue por tres años con la intención de ir a la par con los tiempos del CONACYT.
Lamentablemente, hubo un retraso de aproximadamente 8 meses en el depósito de los recursos debido al tiempo que se requirió por parte de la SEP para la designación del Secretario Administrativo del FSIE, lo cual afectó nuestra organización. De hecho, el CONACYT nos otorgó en forma automática una prórroga de seis meses en nuestro proyecto. De esta manera, ante dicha institución el proyecto termina oficialmente en junio de 2016 (aunque pediremos una prórroga para terminar en diciembre del mismo año). Lamentablemente, el registro ante el Consejo Divisional ya se había hecho efectivo, por lo que no se pudo actualizar los tiempos.
Todo lo anterior tuvo como consecuencia un desfase de casi un año, lo cual ha llevado a algunos retrasos en nuestros planes originales. Además, Edgar Morales, uno de los estudiantes de doctorado de la UNAM que desde un inicio ha participado en este proyecto, contrajo una seria enfermedad. Ello también ha contribuido a retrasos.
A pesar de las demoras descritas, el Grupo Interdisciplinario en Creatividad Computacional fue capaz de cumplir en términos generales con todos los objetivos que se plantearon. Sin embargo, quedan algunos pendientes que quisiéramos terminar. Por ello, se anexa a este reporte una solicitud de prórroga. El documento está organizado como sigue. La sección *Resultados* detalla los productos generados a lo largo del proyecto; la sección *Análisis de los objetivos del proyecto* describe cada uno de los objetivos y explica su estado actual.

Resultados

En esta sección se analiza los productos académicos generados y se contrastan con los compromisos adquiridos. Cabe aclarar que estamos incluyendo algunos productos que se han publicado después de julio de 2015. La razón es que el trabajo necesario para llevarlos a cabo ocurrió antes de la fecha de terminación de este proyecto.
Se publicaron 24 textos, se organizaron 3 eventos internacionales (un cuarto está a punto de efectuarse) y se editó un libro interdisciplinario. La tabla 1 muestra a detalle cada uno de los productos generados y se contrasta con los objetivos planteados al inicio del trabajo.
En lo que respecta al número de revistas indizadas, actualmente tenemos cinco publicaciones y dos en revisión. Nuestro compromiso para el último año era haber enviado ocho documentos (recalcamos que el compromiso fue “enviar” ya que el proceso de dictaminación en el área tarda en promedio un año y medio, por lo que es imposible tener publicados todos los textos al final del proyecto). De esta manera, sólo tenemos pendiente un artículo el cual pensamos terminar durante

la ampliación de este proyecto. En lo referente a artículos en extenso publicados en congresos internacionales hemos excedido en tres el número prometido. Cabe resaltar que cada uno de dichos textos fueron artículos completos (no resúmenes) sometidos a un proceso de tres arbitrajes por miembros de comités académicos internacionales. A pesar de que no había el compromiso explícito, también produjimos tres artículos cortos para congreso, cinco capítulos de libro y uno de divulgación. De esta manera, consideramos que la meta de publicaciones fue plenamente satisfecha. En lo que se refiere a eventos internacionales y edición de libros cumplimos cabalmente con las metas establecidas.

	Compromisos adquiridos al inicio del proyecto	**Artículos Publicados o productos generados**	**Borradores de artículos en revisión**
Revistas indizadas	8	5	2
Congresos (artículos en extenso con arbitraje internacional)	7	10	
Congresos (artículos cortos)	0	3	
Capítulos de libro	0	5	
Artículo de divulgación	0	1	
Eventos Internacionales	3	3 (no se contabiliza el Coloquio de 2015)	
Edición de libro interdisciplinario	1	1	

Tabla 1. Productos generados en el proyecto

Quisiéramos hacer un análisis más detallado de los productos generados. Comenzaremos con la producción de artículos. La tabla 2 muestra un análisis por año de los textos que tenemos publicados. Como se puede observar, a medida que fue avanzando los trabajos aumentaron el número de publicaciones hasta obtener los máximos hacia el final del proyecto.

Nuestro trabajo es interdisciplinario, lo cual conlleva dos características principales: el desarrollo de trabajo colectivo y la retroalimentación a cada disciplina participante de los conocimientos generados por el grupo. En el primer caso promovemos la publicación de textos entre dos o más autores; en el segundo caso pugnamos por la publicación en solitario. Ésta última nos parece fundamental si deseamos que los miembros del grupo se apropien desde una perspectiva disciplinar de los conocimientos generados colectivamente. La tabla 3 muestra una relación entre el número de artículos publicados y el número y características de los autores. Como se puede observar, 7 de los 24 artículos (29%) fueron publicados por un solo autor. Tenemos el mismo número para artículos publicados por dos o más miembros del grupo que pertenecen a diferentes departamentos, y por miembros del grupo con colegas de otras instituciones (las cuales son MIT, Harvard, Universidad de Singapur, UNAM e ITAM). De esta manera, 17 de dichos textos (71%) fueron publicados por dos o más autores, lo cual claramente habla de una vocación colectiva sin descuidar el trabajo individual para la apropiación del conocimiento.

Cabe mencionar que en este momento estamos en proceso de organización del 10º Coloquio Internacional en Creatividad Computacional.

En lo que se refiere al libro interdisciplinario, el 3 de noviembre se presenta como parte de los festejos del 10º aniversario de nuestra Unidad la obra Creatividad Computacional. A continuación la descripción del mismo:

> *Creatividad Computacional* es el primer libro escrito en español acerca de esta novedosa y fascinante área del conocimiento, cuyo objetivo es contribuir al entendimiento del proceso creativo empleando para ello modelos computacionales. En sus páginas, el lector encontrará interesantes descripciones de sistemas que desarrollan narrativas, construyen y tuitean metáforas o crean nuevos conceptos. Evitando en la medida de lo posible un lenguaje técnico, esta obra presenta un enfoque interdisciplinario que debe despertar interés en aquellos estudiosos de las humanidades, las ciencias sociales, el arte y las ciencias de la computación. Todos los autores son académicos de gran renombre en universidades de Europa, Estados Unidos y México. De esta manera, la UAM Cuajimalpa y el Grupo Editorial Patria ponen a disposición de los lectores hispanoparlantes conocimientos de vanguardia que sin duda ejercen una gran influencia en nuestra sociedad (cuarta de forros, Creatividad Computacional Pérez y Pérez 2015.

Queremos recalcar la calidad de los autores que participan y el hecho de que éste constituye el primer libro en español sobre el tema. Nuestro proyecto ocupa tres capítulos del mismo. De esta manera, nuestra investigación se sitúa al mismo nivel que otros trabajos con gran reconocimiento internacional, y hemos colocado a la UAM Cuajimalpa, y en particular a la DCCD, como un referente en Latinoamérica de la Creatividad Computacional.

Participantes en el proyecto

Al inicio del proyecto se registraron los siguientes participantes:
Responsable: Dr. Rafael Pérez y Pérez
Participantes internos: Dra. María González de Cossío, Mtra. Nora Morales, Dr. Vicente Castellanos, Dr. Eduardo Peñaloza, Dr. Santiago Negrete, Mtro. Rafael Ávila, Mtro. Otoniel Manuel Ortiz Ruiz.
Participantes externos al proyecto: Edgar Morales, Wendy E. Aguilar e Iván Guerreo (Estudiantes de doctorado de la UNAM).

Fueron dados de baja: El Mtro. Otoniel Ortiz, quien decidió estudiar un doctorado; la Mtra. Nora Morales y el Dr. Santiago Negrete por diversas causas (ver cartas anexas).

Análisis de los objetivos del proyecto

1. Desarrollo de un modelo cognitivo/computacional para la generación de narrativas que expanda las ideas de E-R.
Los trabajos desarrollados han permitido representar mecanismos cognitivos para la apropiación del conocimiento y la construcción de significados a partir de las narrativas construidas por el sistema. Se han publicado los resultados.

	2012	2013	2014	2015	Totales
Revistas indizadas	1	2		2	5
Congresos (artículos en extenso con arbitraje internacional)	1	4	4	1	10
Congresos (artículos cortos)			3		3
Capítulos de libro				5	5
Artículos de divulgación			1		1
Totales por año	2	6	8	8	**24**

Tabla 2. Relación de artículos publicados por año.

Artículos con un autor	7
Artículos con 2 o más autores del mismo departamento	1
Artículos con 2 o más autores de diferente departamento	7
Artículos con autores de otras instituciones	7
Artículos sólo con estudiantes como coautores	2

Tabla 3. Características de los textos publicados

Nos parece importante resaltar que todos los miembros del grupo han participado en al menos una publicación relacionada con el proyecto. De esta manera hemos logrado una integración adecuada.

En lo que se refiere a la realización de eventos internacionales, hemos cumplido con organizar uno cada año. Hemos traído expertos con amplio reconocimiento internacional de las principales universidades de Europa y Estados Unidos. A continuación los detalles:

2012: 7º Coloquio Internacional en Creatividad Computacional
Dr. Amilcar Cardoso
Universidad de Coimbra, Portugal

2013: 8º Coloquio Internacional en Creatividad Computacional
Dr. Nick Montfort, MIT
Dr. Fox Harrell, MIT
Dr. Sneha Veeragoudar, MIT

2014: 9º Coloquio Internacional en Creatividad Computacional
Dr. Mark Turner, Case Western Reserve University, USA
Dr. Tony Veale, University College Dublin, Ireland
Dr. Geraint Wiggins, Queen Mary University of London, UK

Nuestra División, así como la Unidad, se han beneficiado de diversas maneras de estos eventos: hemos tenido la oportunidad de escuchar de primera mano los trabajos más recientes de este grupo de científicos; todos ellos implican trabajo interdisciplinario, por lo que hemos podido observar y analizar diversos ejemplos sobre cómo se lleva a cabo la interdisciplina; los alumnos de la MADIC han recibido de estos investigadores una retroalimentación sobre sus trabajos de idónea comunicación humana; se han organizado diversos talleres dirigidos a alumnos y profesores impartidos por los invitados; se han llevado a cabo reuniones de trabajo con investigadores de la División; se han fortalecido las redes académicas de la División; entre otros.

Tenemos desarrollado un 50% del modelo para representar procesos de generalización y abstracción del conocimiento. Lamentablemente, Edgar Morales, la persona a cargo de esta tarea, tiene serios problemas de salud que le han impedido avanzar como esperábamos.

2. Desarrollar instrumentos que permitan obtener en forma automática un conjunto de normas y reglas de comportamiento las cuales se integren a la base de conocimientos de los agentes y representen en forma explícita el conocimiento social.
Este modelo está terminado. Ya se han publicado los resultados. Decidimos avanzar estos trabajos por lo que nos hemos dedicado a desarrollar herramientas de análisis que nos permita explotar mejor la información generada.

3. Desarrollar un modelo computacional que les permita a los agentes evaluar qué tan interesantes y novedosas son las historias que producen en forma individual o colectiva.
El modelo está terminado. Los resultados han sido publicados. Estamos interesados en ampliarlo con los nuevos hallazgos que estamos generando.

4. Diseñar un modelo computacional que permita el desarrollo de narrativas visuales basadas en las historias producidas por Mexica y Mexica-Impro.
Etapa 1: Se generó una gramática para lograr este objetivo. Se produjeron 197 imágenes que emplea un programa de cómputo para ilustrar en forma automática narrativas.
Etapa 2: En una segunda etapa se desarrolló un modelo de composición visual el cual permite romper la rigidez de la gramática desarrollada en la primera etapa. Los resultados de este último trabajo han sido publicados.

5. Realizar un análisis de cómo modelos como el E-R y México-impro pueden contribuir al estudio de la comunicación social.
Se han publicado dos artículos al respecto.

6. Integrar todos los modelos desarrollados en una sola plataforma informática.
Todos los desarrollos informáticos están integrados.

7. Realizar una integración teórica interdisciplinaria de áreas de la comunicación, el diseño, el análisis de procesos cognitivos y la inteligencia artificial, como base para modelar improvisación computacional colaborativa.
Esta integración se ha realizado parcialmente. Estamos interesados en generar un documento final que conjunte todas estas ideas.

8. Evaluar los modelos teóricos que fueron fundamento para el desarrollo de los programas de improvisación, narración y construcción de significados
Estas evaluaciones han sido parte de los desarrollos de los modelos y están reportadas en los artículos publicados.

Artículos publicados

2015

• Peñalosa, E. (2015). Interacciones entre la creatividad computacional y la cognición, y su impacto en el desarrollo de teorías. En R. Pérez y Pérez (ed.) *Creatividad Computacional*, UAM-Cuajimalpa-Patria.

• Castellanos, V. (2015). Lecciones entre las ciencias de la comunicación y la creatividad computacional. En R. Pérez y Pérez (ed.) *Creatividad Computacional*, UAM-Cuajimalpa-Patria.

• Pérez y Pérez R. (2015). MEXICA-impro: Generación automática de narrativas colectivas. En R. Pérez y Pérez (ed.) Creatividad Computacional, UAM-Cuajimalpa-Patria.

•Pérez y Pérez, R. (2015). A Computer-based Model for Collaborative Narrative Generation. Cognitive Systems Research, http://dx.doi.org/10.1016/j.cogsys.2015.06.002

• Pérez y Pérez R. (2015). From MEXICA to MEXICA-Impro: The Evolution of a Computer Model for Plot Generation. In T.R. Besold, M. Schorlemmer, A. Smaill (Eds.), Computational Creativity Research: Towards Creative Machines, Atlantis Thinking Machines 7, DOI 10.2991/978-94-6239-085-0_13.

• Pérez y Pérez R. (en prensa). Reflexiones sobre cómo incorporar el trabajo interdisciplinario en la enseñanza universitaria. En Vicente Castellanos (Ed.) Comunicación: Diálogos interdisciplinarios emergentes, México D. F.: UAM Cuajimalpa. (ISBN en trámite).

• Aguilar, W. & Pérez y Pérez, R. (2015). Dev E-R: A computational model of early cognitive development as a creative process. Cognitive Systems Research, 33, pp. 17–41(ISSN: 1389-0417).

• Guerrero, I., Verhoeven, B., Barbieri, F., Martins, P., Pérez y Pérez, R. (2015). The Riddler Bot: a next step on the ladder towards creative Twitter bots. In Proceedings of the Sixth International Conference on Computational Creativity, Park City, Utah, USA, pp. 315-322. http://computationalcreativity.net/iccc2015/

2014

• Pérez y Pérez, R. (2014). The Three Layers Evaluation Model for Computer-Generated Plots. In Proceedings of the Fifth International Conference on Computational Creativity, Ljubljana, Slovenia, pp. 220-229. (http://computationalcreativity.net/iccc2014/proceedings/). (ISBN: 978-961-264-055-2)

• Guerrero-Román, I. and Pérez y Pérez, R. (2014). Social Mexica: A Computer Model for Social Norms in Narratives. In Proceedings of the Fifth International Conference on Computational Creativity, Ljubljana, Slovenia, pp. 192-200. (ISBN: 978-961-264-055-2) (http://computationalcreativity.net/iccc2014/proceedings).

• Gómez de Silva Garza, A., and Pérez y Pérez, R. (2014). Towards Evolutionary Story Generation. In Proceedings of the Fifth International Conference on Computational Creativity, Ljubljana, Slovenia, pp. 332-335. (http://computationalcreativity.net/iccc2014/proceedings/). (ISBN: 978-961-264-055-2)

• Aguilar, W., and Pérez y Pérez, R. (2014). Criteria for Evaluating Early Creative Behavior in Computational Agents. In Proceedings of the Fifth International Conference on Computational Creativity, Ljubljana, Slovenia, pp. 284-287. (ISBN: 978-961-264-055-2) (http://computationalcreativity.net/iccc2014/proceedings/).

• Gómez de Silva Garza, A. Cambria, E. Pérez y Pérez, R., (2014). Commonsense Knowledge As The Glue In A Hybrid Model Of Computational Creativity, Proceedings of the 4th Sentiment Elicitation from Natural Language Text for Information Retrieval and Extraction (SENTIRE) Workshop of the 14th IEEE International Conference on Data Mining (ICDM'14), pp.360-364.

• Ávila, R. y Pérez Y Pérez, R. (2014). Teoría de la comunicación y creatividad computacional: conceptos y convergencias. En Memorias del IV Congreso Internacional de la Asociación Española de Investigación de la Comunicación, Bilbao, España, pp. 1807-1817 (ISBN: 978-84-695-9434-6) (http://www.aeic2014bilbao.org/download/aeic2014bilbao_comunicaciones.pdf)

2013

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Reflexiones para el cierre del proyecto

Modelo Computacional para el Estudio de la Generación Colaborativa de Narrativas Textuales y Visuales

Grupo Interdisciplinario en Creatividad Computacional, UAM Cuajimalpa

Introducción

El modelo E-R está basado en las ideas expresadas por diferentes investigadores y que Mike Sharples recolecta y emplea para describir cómo funciona el proceso creativo cuando escribimos (Sharples 1999). En forma muy general, los conceptos desarrollados por Sharples se pueden resumir de la siguiente manera: el proceso creativo consiste en un ciclo constante entre dos estados mentales conocidos como Estado-E y Estado-R. Durante el Estado-E las personas estamos totalmente inmersas en la generación de secuencias de nuevas ideas por medio de asociaciones: una idea produce un contexto que nos lleva a asociar otra nueva idea, la cual lleva a otra nueva, y así sucesivamente. Un típico ejemplo del Estado-E es soñar despierto, donde claramente se observa cómo una idea se liga a otras a veces aparentemente sin conexión alguna entre ellas; este tipo de asociaciones permite ir desarrollando en forma novedosa un texto en la cual se está trabajando. Como característica principal, durante este período no hacemos ningún tipo de evaluación sobre el material generado, simplemente dejamos que fluyan las secuencias de ideas. El Estado-E se interrumpe cuando somos distraídos por alguien o por algo, o cuando no podemos generar más material produciéndose un bloqueo de ideas. Durante el Estado-R evaluamos que el material generado satisfaga los requerimientos de la tarea en marcha (no es lo mismo escribir un cuento para niños que un cuento de terror); en caso necesario modificamos el material producido para satisfacer dichos requerimientos. Esta evaluación produce una serie de lineamientos o constricciones que condicionan la generación de material durante el Estado-E. Por ejemplo, si una persona está escribiendo un cuento muy aburrido, esta evaluación lo alerta para así tratar de asociar eventos más interesantes. Una vez que se han completado las evaluaciones volvemos al Estado-E y el ciclo continúa.

2. Desarrollo

MEXICA (Pérez y Pérez 2007) es un agente computacional el cual, con base en el Modelo ER, genera argumentos de historias cortas sobre los mexicas. MEXICA-impro es un modelo computacional para la generación colectiva de narrativas entre, al menos, dos agentes computacionales (ver Pérez y Pérez et al. 2010; Pérez y Pérez et al. 2011; Pérez y Pérez y Ortiz 2013). Es decir, queremos que dos Mexicas, en equipo, generen una narrativa que sea coherente, interesante y novedosa. La figura 1 muestra na narrativa generada por el sistema.

Hace algunos años la virgen nació bajo la protección del gran dios Huitzilopochtli. El caballero ocelote era un miembro respetado de la sociedad mexica. Desde el primer día que se conocieron el caballero ocelote sintió una gran admiración por la virgen. Aunque al principio no lo aceptaba, él se enamoró de la virgen. El caballero ocelote tenía un gran afecto por la princesa. La virgen tenía un gran afecto por la princesa. La virgen era una persona ambiciosa y decidió raptar a la princesa. El caballero ocelote estaba emocionalmente ligado a la virgen pero no pudo aceptar el comportamiento de la virgen. Mientras viajaba el caballero ocelote encontró accidentalmente a la virgen. El caballero ocelote la observó cuidadosamente y luego la atacó. Con un movimiento rápido la virgen hirió al caballero ocelote. La virgen sintió pánico y huyó hacia el Popocateptl para esconderse

Figura 1. Narrativa producida por MEXICA (traducida del inglés por los autores).

Como característica importante, cada uno de ellos tiene su propia base de conocimientos. Además, empleamos una representación computacional de aspectos culturales como son las normas sociales, para así dar la oportunidad de que puedan compartir algunas de dichas normas o tener las suyas propias. De esta manera, al momento de crear una nueva narrativa cada Mexica está influenciado por la representación computacional de su carga cultural. Para este proyecto, hemos planteado la siguiente hipótesis operativa:

> Si dos agentes computacionales tienen la misma representación cultural —mismas normas y misma jerarquías sociales— generarán un número menor de narrativas novedosas e interesantes que dos agentes con diferentes representaciones culturales. Si dos agentes computacionales tienen representaciones culturales demasiado diferentes, no serán capaces de producir narrativas coherentes, y por lo tanto ni novedosas ni interesantes. De lo anterior concluimos que, para generar las narrativas más novedosas e interesantes, es necesario contar con representaciones culturales diferentes sin que estas diferencias sobrepasen un punto límite. Este punto límite ocurre cuando la diferencia en la base de conocimiento de los narradores computacionales es tan importante que la comunicación entre ellos se vuelve ininteligible.

La interacción entre los agentes está organizada de la siguiente manera. Uno de ellos tiene el papel de líder y el otro el de acompañante o seguidor. La función del líder es iniciar el desarrollo de la narrativa e indicar cuándo ésta ha terminado; la labor del seguidor es secundar al líder con el desarrollo de la historia. Así, el líder inicia el relato y se la comunica al seguidor en forma de texto; el seguidor interpreta dicho texto y hace su propia contribución para avanzar el cuento. A continuación, le regresa el texto actualizado al líder quien lo interpreta y vuelve a iniciar el ciclo. El proceso continúa hasta que el líder no sabe cómo proseguir el cuento o considera que éste está terminado. En nuestro proyecto, el proceso de interpretación consiste en convertir un texto en estructuras computacionales que los agentes puedan manipular fácilmente con el objetivo de producir una narrativa. Dado que cada agente tiene su propia base de conocimientos, es posible que un mismo texto sea interpretado de forma diferente por cada uno de ellos (ésta es una de las características principales de este proyecto). Como es de esperarse, el líder ejerce una gran influencia en el desarrollo de los cuentos.

Nuestros agentes son capaces de evaluar la novedad, la coherencia y el interés de cada una de las narrativas que ellos mismos producen. La figura 2 muestra un ejemplo de dicha evaluación de la crónica que se muestra en la figura 1.

EVALUACIÓN.
Es necesario que trabajes más duro para mejorar algunos aspectos de tu escritura. Aquí encontrarás comentarios que espero sean una buena retroalimentación para ti.

COHERENCIA
La historia es muy lógica; todas las acciones están bien integradas y forman una unidad coherente. Es necesario que todos los conflictos que los personajes afrontan sean solucionados en la parte final del relato. Debes poner una mayor atención a este punto.

INTERÉS
El texto tiene una buena introducción. La historia alcanza un clímax adecuado; ésta es una característica importante de una buena narrativa. ¡Bien! Lamentablemente, tiene un mal cierre que daña su evaluación final.

NOVEDAD
Encuentro esta historia muy original. ¡Me encanta!

Tomando en consideración estos comentarios te otorgo de calificación un 61/100.

Figura 2. Evaluación automática de la historia de la figura 1 producida por MEXICA-impro.

El agente también tiene la capacidad de sugerir cambios a la narrativa final. Por ejemplo, en este caso detecta que la acción "La virgen tenía un gran afecto por la princesa" no encaja bien con el resto de los acontecimientos y sugiere que sea eliminada. Una meta importante del proyecto es que cualquier cuento desarrollado de manera colaborativa no pueda haber sido creado en forma individual por alguno de los participantes. De otra manera, ¿cuál es el caso del trabajo en equipo?

El sistema incluye un módulo que le permite ilustrar sus narrativas (ve figura 3). Por medio de una gramática desarrollada para tal propósito, y dependiendo de las circunstancias afectivas que rodean a los personajes (por ejemplo, si están enamorados, si se odian, entre otras), MEXICA-impro genera una ilustración para cada acción que ocurre en una historia.

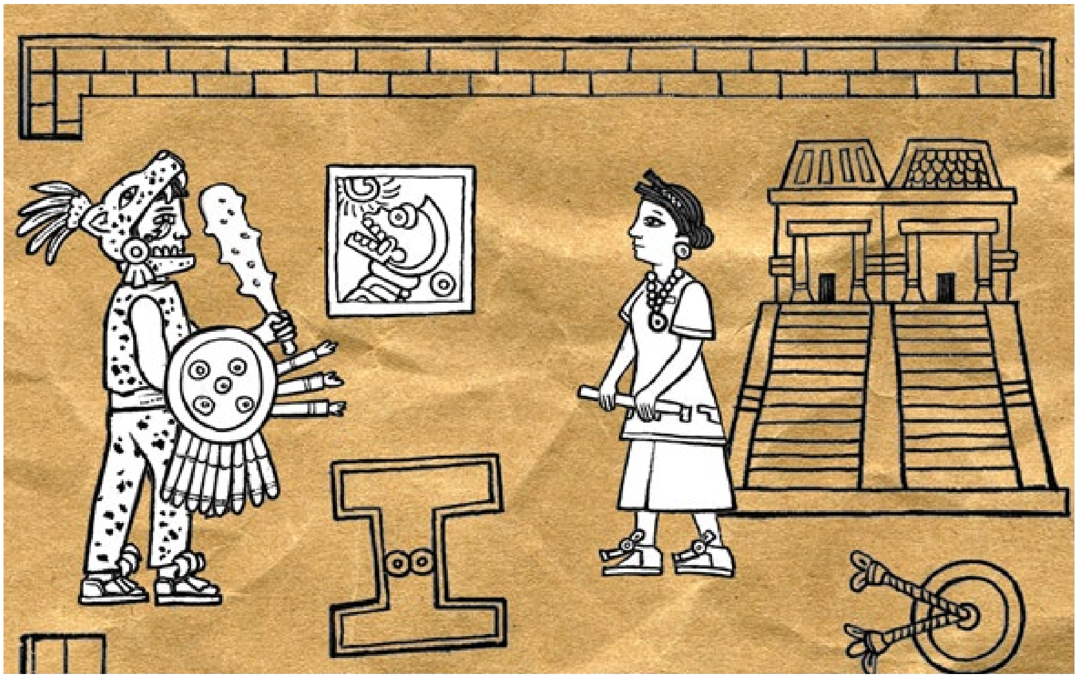

Figure 3. Ejemplo de la ilustración de una escena producida por MEXICA-impro.

El diseñar una representación computacional de normas sociales ha involucrado, entre otras cosas, el relacionar explícitamente algunas de las características que los expertos en ciencias sociales emplean al trabajar con dichas reglas, con los procesos que conforman el modelo cognitivo usado por los agentes computacionales, así como con los aspectos técnicos necesarios para su implementación en un programa informático. Al entender cómo surge esta relación y sus consecuencias en nuestro modelo, hemos logrado que las representaciones computacionales de las normas tengan un peso específico en las narrativas generados por nuestros agentes. Esta conjunción de ideas y visiones son el origen de nuestra hipótesis operacional. Para probarla, desarrollamos algoritmos que permiten comparar las bases de conocimientos de los agentes y así establecer una medida de similitud entre las normas sociales de cada uno de ellos. Con ello pretendemos encontrar el punto límite, aquel donde los agentes son más creativos pero siguen en condición de poder comunicarse entre ellos. Esto nos ha llevado a distinguir entre conocimiento normativo —conocimiento que depende de un contexto cultural o social— y conocimiento lógico —conocimiento que es independiente de un contexto cultural y por lo tanto es igual en todos los grupos sociales— dentro del marco de un modelo computacional de interacción social.

La metodología que hemos desarrollado para comparar las bases de conocimiento de los agentes permite visualizar, para cada uno de ellos, qué tan similares entre sí son cada una de las estructuras que conforman dicha base, y qué tanto conocimiento comparten ambos agentes. Con esta información establecemos relaciones entre las características de los saberes de cada agente, la sabiduría compartida y el tipo de crónica que generan tanto en forma individual como colectiva. Nuestra principal conclusión es que no existe un solo punto límite donde se obtienen las mejores narrativas colaborativas, como lo sugiere nuestra hipótesis operacional, sino diversas posibilidades que dependen de la experiencia de los agentes y del papel que juegan, ya sea de líder o de seguidor, al momento de producir un nuevo relato.

Comunicación, diseño e inteligencia artificial.

Este trío parece tener poco en común. Las palabras que lo componen podrían representarse por medio de tres personajes estereotípicos, una para cada palabra. Así la comunicación podría ser representada por un personaje como por ejemplo, el creativo de una agencia publicitaria, cabello largo, un toque hipster; el diseño sería representado por una diseñadora de cabello suelto, vestida de manera original y muy a la moda y la Inteligencia artificial sería representada por… bueno, cuesta trabajo crear un personaje adecuado para esta disciplina. Esto puede deberse a su juventud o a su poca visibilidad fuera de círculos muy restringidos de expertos y científicos. Así que es probable que nuestra creatividad para generar a este personaje sea limitada por esta falta de una imagen definida de esta disciplina. Sin embargo sus dos componentes “inteligencia” y “artificial” apuntan de suyo a una suerte de limbo abstracto, indefinido, frío y…. un tanto mecánico. Ahora bien si la IA es este ser desencarnado ¿cómo podría sentarse a la mesa con nuestros “muy humanos” y “creativos” comunicólogo y diseñadora?, ¿qué podrían hacer los tres sentados a la mesa, café de por medio?. Es difícil imaginar una narrativa en la que los tres personajes interactúan y nos mantienen interesados en sus acciones, sus tensiones y la solución de las mismas. En resumen, es difícil imaginar a este trío conversando animadamente en un café. ¿Cómo podrías resolver esta dificultad de la imaginación?, ¿podríamos tener una herramienta que nos ayudará a: diseñar al personaje que nos falta; ayudarnos a narrar una pequeña historia sobre su encuentro en el café con los otros dos; hacer que la narración sea interesante?

Esta es una herramienta tan impensable para muchos como para nosotros la creación de nuestro personaje: sin embargo veamos que puede hacer este personaje incorpóreo y abstracto, llamado inteligencia artificial, para ayudarnos con nuestro problema creativo.

Hoy en día la inteligencia artificial es capaz de generar narrativas creando personajes y tramas a partir de conjuntos de datos y condiciones para su desarrollo. Así, nuestro frío y abstracto personaje fantasmal podría aparecer como un "creativo" que se autogenera y propone una narrativa desarrollada entre los tres personajes citados.

La creatividad y en especial, la narrativa, siempre ha estado conceptualizada como una esfera de lo "humano". La narrativa social impuesta sobre el tema nos presenta a unos seres humanos excepcionalmente humanos que se nos aparecen como "únicos', "diferentes", etc… La oposición histórica entre el mundo de los objetos, mecanizables, hiperracionalizados, cuantificables en todas sus dimensiones, repetitivos, ciegos, etc… y el mundo subjetivo poblado de imágenes mentales, emociones, fantasía, libertad, de lo que se nos ha querido presentar como lo propiamente "humano", parece contradecirse cuando hablamos de un programa de inteligencia artificial capaz de "crear" historias, personajes, etc… El sentido común nos dice que la IA pertenece al ámbito de lo mecánico, de la fría racionalidad, etc.. Por lo tanto, es nuestra facultad imaginativa la que se rehúsa a aceptar a la IA sentada a la mesa de dos profesionales que han llegado a representar la capacidad creativa puesta al servicio de la funcionalidad, la empresa, o la sociedad. Ante el hecho de que efectivamente, la IA ha generado programas capaces de narrar historias, crear personajes, y hasta evaluar su calidad narrativa, es necesario replantear tanto al concepto "creatividad" como las profesiones que típicamente se dedican a generar productos por esa vía.

Una alternativa es ir de las máquinas y los programas hacia el ser humano, es decir, podemos pensar que las máquinas están logrando "humanizarse" en algún sentido y siguiendo la lógica apocalíptica que quisiera ver amenazada a la especie humana, sentir un escalofrío ante la amenaza de ser sustituidos por máquinas, etc…. Otra vía es ir de los seres humanos hacia la IA, me refiero a que quizá esa "creatividad" humana fue mitificada y nunca fue en realidad un ámbito que escapara de la lógica y del sistema. En esta versión podemos pensar que el trabajo del artista renacentista o barroco, el trabajo ya no del individuo único sino del taller grupal, del método, de la repetición como recurso y no como traición al origen se habría impuesto sobre aquél artista romántico que la imaginación popular sigue enalteciendo en su afán por mitificar al "artista".

Y sin embargo, habría una tercera vía más allá de las oposiciones tradicionales. Esta sería una vía abierta en dos direcciones. En la primera el "creativo – humano" se abre a las posibilidades que le ofrecen los programas de IA para comprender mejor su propia actividad, se pone ante un espejo que lo obliga a ver sus limitaciones creativas y las restricciones que la misma rutina creativa le habría impuesto. En la otra dirección, el creativo recurre a los programas de IA como herramienta a su servicio, éstos le ofrecen materiales, posibilidades técnicas y mecánicas liberándolo para abrir otras formas de pensar, otras formas de comprensión de los fenómenos de diseño y comunicación complejos y los soluciona sirviéndose de la tecnología a su alcance.

Los avances de la IA en el ámbito de la creatividad computacional nos obligan a reconocer los límites de las disciplinas "creativas" tanto comunicacionales como diseñísticas y a replantear su rol en la sociedad actual. La investigación en creatividad computacional y el desarrollo de las capacidades "creativas" de estos programas no hacen evidente la necesidad de explorar otros ámbitos de desarrollo para estas disciplinas, ámbitos que están más allá de la "creatividad" como se ha entendido hasta ahora. Así, el comunicólogo y la diseñadora de nuestra escena pasarían a ser un nuevo tipo de profesional que ya no se define ni por su talento creativo ni por sus capacidades "artesanales". Estas profesiones se transformarán en especialistas en el análisis, la valoración, y la dirección de fenómenos complejos tanto de comunicación como de diseño. Para lograrlo deberán familiarizarse con lo que está sucediendo en su entorno a partir de la IA y establecer un diálogo fructífero que haga crecer a este trío.

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Analysis of the correlations between the knowledge structures of an automatic storyteller and its literary production

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Abstract

In this paper, we describe a process to identify relations among the features of the knowledge base of an automatic storyteller and the narratives that it generates. We define structures to analyze the internal composition of the information available for an agent. We also establish a set of metrics to identify diverse story characteristics. Next, we perform experiments utilizing Mexica, an automatic storyteller, to generate narratives and to evaluate them according to our set of metrics. Then, we compare such assessments with the visual structures that we built from the agent's original knowledge base, in order to obtain correlations between them. The results suggest that such correlations are useful to study the links between the agents' knowledge base and the kind of stories they might produce.

Introduction

During the last 15 years, members of our research group have developed a wide variety of models related to storytelling, and we have implemented them in computational programs, or agents. Among these models there is an automatic storyteller, Mexica, and a collaborative story generator, Mexica-Impro; models for evaluating stories and for identifying social norms in the generated outputs. In all of them, the knowledge structures (KS) available in each of the agents have played an essential role. We have utilized emotional and tension links between the characters in a story to represent these KSs, and we have obtained this information from two major sources: a dictionary of story-actions, and a set of previous stories (narratives written by humans that are considered benchmarks four our models). Nevertheless, one pending task, tackled in this work, is the study of how features of the agents' knowledge base influence the narratives that they generate. The direct antecedents of this research arise from a three-fold base: automatic story generation and evaluation, and description of high-level structures emerging from the knowledge bases of our agents.

From the first text generation works in the early 60's (Klein 1965), to the latest storytellers such as Fabulist (Riedl 2004), Mexica (Pérez y Pérez 2001 and 2007) or Minstrel (Turner 1994), automatic narrative generation has intrigued researchers for decades in an attempt to better understand diverse aspects of this process. Despite the fact that they have descriptions of how internally represent their knowledge, it is commonly missing how these structures affect the overall quality of the generated stories. Moreover, they lack of high-level representations of the available knowledge to identify emergent structures, and to analyze how these structures prevent unpleasant behaviors and promote desirable features in their outputs.

Regarding to the evaluation of the generated stories, Pérez y Pérez (2014) proposed a layered model describing how features such as opening, climax, closure... in a story, could be measured to determine how coherent, novel and interesting they are. In our work, we rely on these metrics and extend them to identify additional story features and structural elements of the agent's knowledge bases.

To identify high-level structures of the agent's knowledge, Pérez y Pérez (2015) describes contextual structures maps. They represent how the acquired wisdom of an agent is distributed throughout the space of all the possible structures, and identifies different types of elements according to their number of components. In this work, we build upon this idea to present alternative high-level structures to represent relations according to the similarity among the elements inside the KS of our storyteller.

We claim that if we are able to link previous stories with the agents' KSs, and find out how KSs' features influence the characteristics of the generated plots, we will improve our understanding about the importance of previous experiences for the plot generation process. In this way, our agents will be able to identify for example what type of knowledge is still missing in their repositories, and develop stories to explore specific topics with the purpose of filling these gaps.

In general, we review how Mexica, an automatic storyteller, builds its own knowledge structures, and we present a high-level structure which provides us additional information about the knowledge of the computer agent. Then, we present a set of metrics to describe features of stories generated by an agent implementing Mexica, and we also present features to describe the structure of its knowledge base. Finally, we identify relations between these two different types of features.

In this paper, we describe a methodology to visualize characteristics of the agents' KSs, referred to as connectivity maps (C-maps), to show the similarities among KSs in memory. Then, we illustrate how the topology of such maps affects several features of the computer generated plots.

Next, we present our findings about how these knowledge structures affect diverse features of stories generated by our agents. Finally, we reflect on these results and speculate on possible extensions to this work.

Gathering information

We rely on two main component types to identify the relations that we are looking for: a story generator and story evaluator, a computer program to assess the outputs of the generator. For the first, we utilized Mexica (Pérez y Pérez 1999, 2007, and Pérez y Pérez & Sharples 2001), and we extended it by incorporating Social Mexica (Guerrero and Pérez y Pérez 2014), a computer model for social norms in narratives to provide additional social information to the story generation process. For the second component, we extended a model for evaluating the interestingness of a narrative proposed by Pérez y Pérez (2014). We now describe each of these components.

Generating knowledge structures

Mexica is a storyteller based on the E-R creativity model (Pérez y Pérez 1999), which describes the creative activity of writing as an iterative two-phased process: engagement and reflection. During engagement the agent selects diverse actions to produce a partial story; whereas in reflection, the system evaluates and updates the material previously generated. Additionally, diverse guidelines to constrain the production of material during engagement are set according to the evaluations performed during this stage. This evaluations also serve to determine when a story is considered to be finished. If this is not the case, the system initiates a new engagement stage and the cycle starts all over again until the story is considered to be finished.

Mexica employs two information sources to generate a variety of knowledge structures utilized during the story generation process: a dictionary of story-actions, and a set of previous stories. Actions in the dictionary have associated a name, and a set of preconditions and post-conditions to represent their requirements and consequences when added to a story. These conditions are defined in terms of emotions (such as love or friendship) and tensions (such as life or health at risk, character prisoner...). Every story (either generated or previous) is defined as a sequence of instantiated actions. This occurs when characters (a performer and an optional receiver) are added.

'Virgin fell in love with Warrior', represents a valid instantiated action. Here, Virgin and Warrior represent the characters, and 'fell in love with' corresponds to the action phrase. Some of these actions consist of only one character, like 'Hunter went to the forest'.

We use contextual structures (CS) to represent the knowledge available for our agent. They are built from the previous stories to be further utilized during the generation of new narratives. Mexica internally transforms a story into emotional relations and tensions between characters, and from this representation, called story-context, CSs are extracted. They consist of two elements: a set of relations (emotions or tensions) between characters, and a list of desirable continuations. Figure 1 represents a story-context obtained from the following story: 'Tlatoani (T) was father of the Princess (Ps)', then 'the priest (Pt) made Princess her prisoner'. The link from Tlatoani to Princess, represent a positive friendship relation with high intensity (+3); the link from Princess to Priest, represent a negative friendship relation (representing hate) with high intensity (-3); and the seesaw link from Priest to Princess, represent a tension between them ('Pr' represents the type of tension, prisoner).

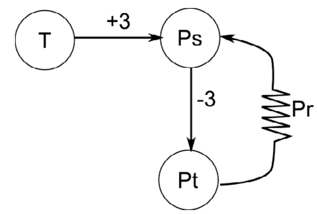

Figure 1: Visual representation of a story-context. Here, nodes represent characters and edges represent relations between characters. The lines with arrow heads represent emotions, whereas the seesaw lines represent tensions.

From the previously described context, Mexica extracts the context of the CS displayed in figure 2. Here, characters are replaced with variables (represented by the letters A, B and C), and the next action in the story is linked to represent a desirable continuation (in our example, the story continued with the action 'T rescued Ps'). A CS can have several actions linked to it. This occurs when identical story-contexts are obtained from different stories, and instead of generating two CS with the same context, we group them into one single CS with multiple actions.

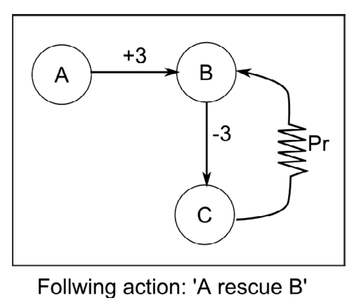

Figure 2: Visual representation of a contextual structure. The rectangle at the top represents a CS-context, and at the bottom is displayed a desirable action for this context.

To identify features related to these knowledge structures, we developed a map to obtain additional information regarding to their similarity. A connectivity map (C-map) represents CSs and relations among them. Every node in this map represents a CS, and two nodes are linked if they are similar enough. The agent determines such similarity by identifying the number of corresponding relations between two structures according to the following rules:

- One emotion is similar to another when they share the same type, valence (positive or negative), and the first has an intensity lower or equal to the second.

- Tensions: Two tensions are similar when they share the same type.
- Once a similar emotion or tension is identified, the character variables of the nodes utilized in the relations are mapped and they cannot be utilized to identify similar relations creating new mappings.

In figure 3, we display a context similar to the one in figure 2. To determine the similarity of the second context with respect to the first, we look for emotions with the same type, valence, and with an intensity lower or equal; we then look for tensions with the same type. In this case, the emotional link between A' and B' in the first context is similar to the emotional link between B and C in the second context. This generates a mapping of the characters A' with B, and B' to C, preventing the generation of new mappings for the variables A', B', B and C. Next, the tension between A' and B' is similar to the tension between B and C, and preserves the original mappings. The only missing element is the emotional link between A and B in the second context. This results in a similarity value of 0.66 (two out of three similar links).

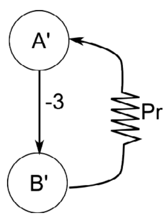

Figure 3: Visual representation of the context in a CS.

From this C-map, nodes are categorized into three different groups according to the number of connections among them. Due to the lack of similar studies, and after analyzing the values obtained, we empirically determined two threshold values of 5% and 10% to create our categories, but we will perform further studies to identify the implications of this values in our study.

- Isolated nodes: Those connected with less than 5% of the total number of nodes
- Regular nodes: Those connected with 5% to 10% of the total number of nodes
- Focal nodes: Those connected with more than 10% of the total number of nodes

When the nodes inside a C-map are linked, they form clusters of similar elements. According to their members, clusters are classified into three categories: islands, towns and cities. After analyzing the number of nodes inside the clusters, we determined two threshold values of 20% and 50% to classify them, but we will develop further studies to determine the implications of this values in our studies.

- Island: Contains less than 20% of the nodes inside the C-map
- Town: Contains between $20-50\%$ of the nodes inside the C-map
- City: Contains more than 50% of the nodes inside the C-map

We present in figures 4 and 5 two samples of C-maps. A gray node represents an isolated node; a red node, a regular; a blue node, a focal. Their size in the picture relies on the number of identical contexts grouped into them. In figure 4, two town-clusters are displayed at the top, and five island-clusters at the bottom of the image. In figure 5, a city-cluster is displayed with an island-cluster at the top.

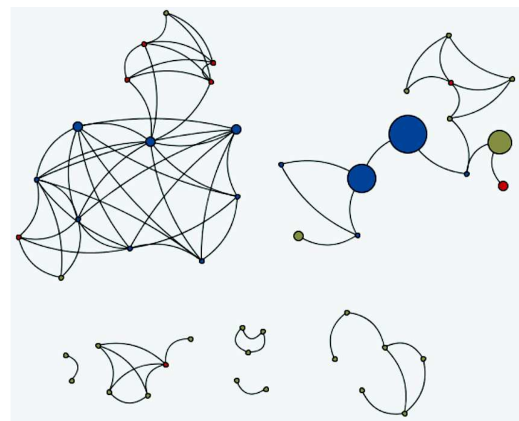

Figure 4: C-map with two town-clusters (top) and five island-clusters (bottom)

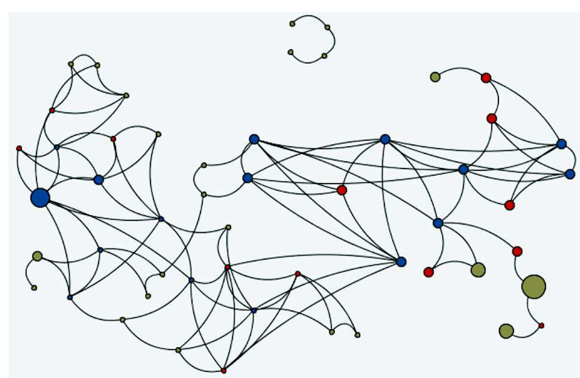

Figure 5: C-map with a city-cluster and an island-cluster

Evaluation process

In grounds of our previous work in this area, we have selected a set of features, known as story-characteristics, for evaluating a plot, and a different set of features, known as structural-characteristics, for evaluating the structures inside the knowledge base of a storyteller.

Evaluating story-characteristics The features utilized to evaluate a story are the following: preconditions fulfilled, novel contextual structures, opening, climax, closure, originality, E-R ratio, number of actions and impasses in a story, character threads and social resolutions. The first eight are part of the feature set described in the evaluation model proposed by Pérez y Pérez (2007 and 2014), and the remaining features are additions to this evaluation model that we considered relevant for this work.

The preconditions fulfilled metric evaluates the number of action requirements satisfied within a story. This value corresponds to a number between 0 and 1 determined by the ratio between the number of preconditions fulfilled for every action versus the total number of preconditions in all the actions.

The novel contextual structures metric determines the amount of new knowledge that a story can generate if it were added to the set of previous stories of an agent. This value is determined by the ratio between the number of new buildable CSs from the story-actions and the total number of CSs that could be generated. We consider a CS new when its context is different from all the existing CSs.

The following metrics are related to the tension curve of a story and to the identification of the three main stages of a story in accordance with the Freytag's pyramid (Freytag 1896). Mexica considers a story to be properly built when it follows this structure. This is why we use it as a reference for these subset of metrics. A story has a correct opening when, at the beginning, there are no tensions and then they begin to grow; it has a correct climax when its highest tension value is similar to a reference value obtained from the set of previous stories; it has a correct closure when all the tensions in the story are solved when the last action is performed.

The originality feature determines the portion of a story that could be generated by the evaluating agent. Mexica is capable of generating a story by itself, from the beginning to a given action, when the following conditions are fulfilled:

1. The story-context associated with the action is similar to the context of one of the available CSs
2. The action is similar to one of the linked actions of the CS with the similar context

The result of this metric is the ratio between the number of actions that could be generated by the evaluating agent, and the total number of actions in a story. If one agent could generate the story on its own, the result is zero; if none of the story contexts are similar to any CS of the agent, the result is one (see figure 6).

$$originality = 1 - \frac{regeneratable\ actions}{total\ number\ of\ actions} \quad (1)$$

Figure 6: Originality

The ER-ratio feature determines the relation between the actions added during the reflection phases versus the actions added during the engagement phases. According to the E-R model, both the engagement and reflective stages should provide a similar number of actions to a story. We claim that a story with engagement actions will be novel, but lack of coherence (since actions requirements are not validated at this stage). On the other hand, a story with reflective actions will be coherent, but lack of novelty (causal constraints are validated during reflection). In general, the result for this metric corresponds to one minus the absolute value of the difference between the engagement ($actions_E$) and reflection ($actions_R$) actions divided by the total ($actions$) number of actions (see figure 7). When the actions added in engagement and reflection are the same, the result is one. When the actions added in engagement or in reflection is zero, the result is zero.

$$ER - ratio = 1 - |\frac{actions_E - actions_R}{actions}| \quad (2)$$

Figure 7: ER-ratio

An impasse occurs when, during engagement, the context of a story is not similar to any context from the available CSs, and the stage finishes. We claim that this behavior occurs when the current story is interpreted as an unknown context for the agent. This feature determines the number of times this situation occurs during the generation of a story.

The character threads feature determines the number of groups (threads) of characters inside the story. We state that two characters belong to a thread when they have a significant relationship inside a story. This condition is fulfilled when two characters participate together in an action that generates or removes a tension between them. For this work, we narrow the number of groups in a story to maintain it simpler and to prevent the existence of parallel stories. The result of this evaluation is a number between 0 and 1 calculated as one divided by the number of character threads inside a story.

The social resolutions feature determines the number of social tensions that remain unsolved by the end of a story. These tensions are added by the Social Mexica component every time a social norm is broken inside a story. We are interested in determining how accurately Mexica finishes these additional tensions within a story in order to fit into the Freytag's pyramidal model. The result of this feature corresponds to the ratio between the number of social tensions solved versus the total number of these tensions in a story. When every social tension was solved, the result is one. When none of the social tensions were solved, the result is zero.

Evaluating structural-characteristics With regards to the knowledge structures, we analyze the C-maps defined to obtain the following set of metrics:

- Percentage of clusters of each type (cities, towns, and islands)
- Percentage of nodes of each type (focal, regular, and isolated)

The percentage of city-clusters describes the ratio between the number of them contrasted against the total number of clusters inside the C-map. Similar calculations are performed to determine the percentage of town-clusters and island-clusters. For the percentage of focal-nodes we count the number of such nodes inside any cluster of the C-map and divide this by the total amount of nodes. We obtain the percentage of regular-nodes and isolated-nodes in a similar way.

Identifying relations

Here, we describe a process to identify relations between the story-characteristics and the structural-characteristics described above.

The relations identified in this work are classified into two categories: cluster ratios and node ratios. In the following paragraphs, we explain the process to identify such relations.

The first step consisted in gathering 40 previous stories and partitioning them into sets. With this, ten stories were located into each set, conforming four story-sets (SS). Then, we split them into two story-banks (SB) with two story-sets each. Next, we recombined the stories on every bank to generate two additional sets, each with 70% of the stories of one story-set and 30% of the stories of the other (see figure 8). We performed the same process in both of the SBs.

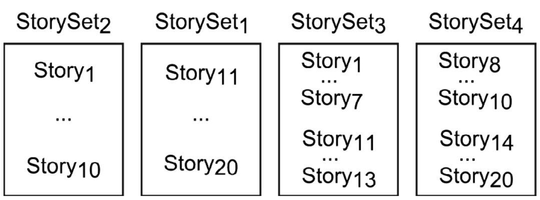

Figure 8: Visual representation of the first SB consisting of four SS. 70% of the stories in SS_3 came from SS_1, and 30% from SS_2. This proportions were inverted to generate SS_4.

After these, we obtained four story-sets on each bank (eight story-sets in total divided into two banks) with the following characteristics:

- Every story-set has totally different stories from one of the story-sets in its story-bank
- Every story-set has 70% similar stories from one of the story-sets in its story-bank
- Every story-set has 30% of stories from one of the story-sets in its story-bank

We utilized each story-set as input for each of the eight different story-generation agents. We let each one of them to generate thirty stories, and we repeated this process three times. By the end of this process, we collected 90 stories per agent. The next step consisted on evaluating every generated story. Each of them was evaluated by every agent in the same bank of the generator, obtaining four evaluations per story. Each evaluation comprised the metrics previously described.

Once these evaluations were completed, we removed those outputs that we did not considered as valid stories according to the following criteria: its preconditions are fulfilled in at least 75%, it has only one character thread, and it contains at least four actions. We collected the evaluations of the remaining stories, obtained the averages for each metric (considering the four evaluations), and we validated if there were differences among them for each of the agents. For this task, we performed an analysis of variance preceded by a K-S test -Kolgomorov-Smirnof test (Massey 1951)- to validate that the data was normally distributed (a request for the variance analysis).

Once we obtained the average values for every metric for every agent, we analyzed the knowledge utilized during the story generation process. The first step consisted in generating the corresponding C-map for every agent to obtain ratios between the different types of nodes and clusters.

We calculated the coefficient of determination (R^2) and the Pearson correlation for every metric utilized during the evaluation process against every metric utilized to describe the knowledge structure. These values leaded us to identify relations between the story-characteristics and the structural-characteristics.

In general, the Pearson-correlation coefficient is a decimal value between -1 and 1. A positive value represents a direct relation between two data sets (when one grows the other does it too), whereas a negative value represents an inverse relation (when one grows, the other decreases), and a value close to 0 represents no linear relation between them. The R^2 value represents how close a data set behaves according to a polynomial of degree n. When $n = 1$, it represents how close is the data to a linear behavior. A value of one for this metric corresponds to a perfect match with a linear behavior, whereas a value of zero represents the absence of a linear correspondence. We now present the relations between every pair of metrics whose values were close to one, which identifies highly related data sets.

Results

Now we present only the results obtained for those relations found between story-characteristics and structural-characteristics with a strong Pearson correlation value (greater than 0.5 or lower than -0.5). The rest of the possible pairings were removed since their Pearson correlation values were not significant. Further studies will determine whether exist additional nonlinear relations among these banned pairings.

In figure 9, we present the novel contextual structures evaluation averages contrasted against the percentage of focal and isolated nodes for each agent. The Pearson correlation values obtained were 0.8 for focal nodes and -0.71 for isolated nodes, and the R^2 values for $n = 1$ were 0.51 and 0.64 respectively. The first values represent a positive linear relation between the novelty of a story and the number of focal nodes inside the story generator, and the second values represent a negative linear relation between the novelty and the number of isolated nodes.

In figure 10, we present the opening averages against the percentage of city and island clusters for each agent. The Pearson correlation values obtained were 0.78 for city clusters and -0.86 for island clusters, and the R^2 values for $n = 1$ were 0.60 and 0.74 respectively. The first values represent a positive linear relation between the opening of a story and the number of city clusters inside the story generator, and the second values represent a negative linear relation

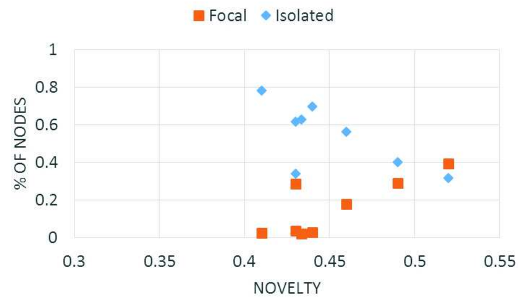

Figure 9: Novel contextual structure averages versus percentage of focal and isolated nodes

between the opening and the number of island clusters.

Figure 10: Opening averages versus percentages of city and island clusters

In figure 11, we present the climax averages against the percentage of focal and isolated nodes for each agent. The Pearson correlation values obtained were 0.83 for focal nodes and -0.85 for isolated nodes, and the R^2 values for $n = 1$ were 0.69 and 0.72 respectively. The first values represent a positive linear relation between the climax of a story and the number of focal nodes inside the generator knowledge base, and the second values represent a negative linear relation between the climax and the number of isolated nodes.

In figure 12, we present the closure averages against the percentage of city and island clusters for each agent. The Pearson correlation values obtained were -0.66 for city clusters and 0.67 for island clusters, and the R^2 values for $n = 1$ were 0.44 and 0.45 respectively. The first values represent a negative linear relation between the closure of a story and the number of city clusters inside the story generator, and the second values represent a positive linear relation between the closure and the number of island clusters.

In figure 13, we present the character threads' averages against the percentage of focal and isolated nodes for each agent. The Pearson correlation values obtained were 0.79 for focal nodes and -0.86 for isolated nodes, and the R^2 values for $n = 1$ were 0.62 and 0.74 respectively. The first

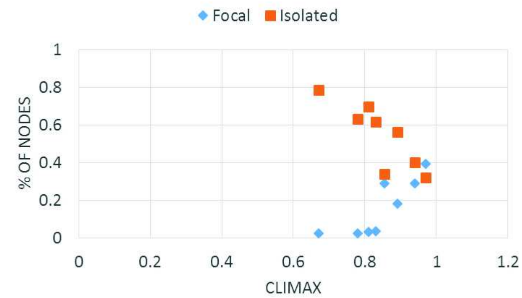

Figure 11: Climax averages versus percentages of focal and isolated nodes

Figure 12: Closure averages versus percentages of city and island clusters

values represent a positive linear relation between the character threads of a story and the number of focal nodes inside the generator knowledge base, and the second values represent a negative linear relation between the character threads and the number of isolated nodes.

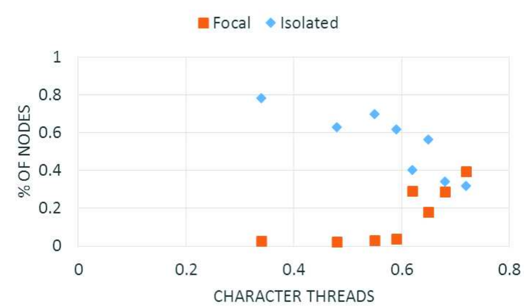

Figure 13: Character threads averages versus percentages of focal and isolated nodes

In figure 14, we present the social resolution averages against the percentage of city and island clusters for each agent. The Pearson correlation values obtained were -0.87 for city-clusters and 0.67 for island-clusters, and the R^2 values for $n = 1$ were 0.75 and 0.45 respectively. The first values represent a negative linear relation between the social resolutions in a story and the number of city-clusters inside the generator knowledge base, and the second values represent a positive linear relation between social resolutions and the number of island-clusters.

Figure 14: Social resolution averages versus percentages of city and island clusters

In figure 15, we present the originality evaluation averages contrasted against the percentage of town and island clusters for each agent. The Pearson correlation values obtained were -0.75 for town clusters and 0.61 for island clusters, and the R^2 values for $n = 1$ were 0.56 and 0.38 respectively. The first values represent a negative linear relation between the originality of a story and the number of town clusters inside the story generator, and the second values represent a weak positive linear relation (since values are not close to 1) between the originality and the number of island clusters.

Figure 15: Originality averages versus percentages of town and island clusters

In figure 16, we present the E-R ratio averages against the percentage of focal and isolated nodes for each agent. The Pearson correlation values obtained were 0.87 for focal nodes and -0.86 for isolated nodes, and the R^2 values for $n = 1$ were 0.75 and 0.73 respectively. The first values represent a positive linear relation between the E-R ratio and the number of focal nodes inside the generator knowledge base, and the second values represent a negative linear relation between the E-R ratio and the number of isolated nodes.

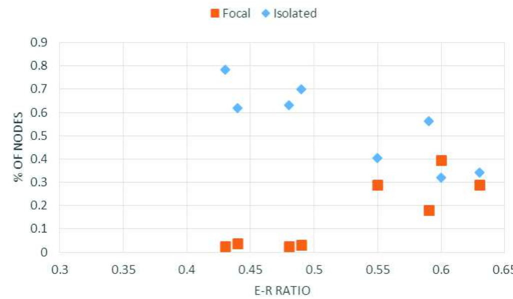

Figure 16: E-R ratio averages versus percentages of focal and isolated nodes

In figure 17, we present the average story size (in actions) contrasted against the percentage of focal and isolated nodes for each agent. We also present the average number of impasses against the percentage of regular nodes for each agent. The Pearson correlation values obtained were 0.87 for focal nodes, -0.86 for isolated nodes, -0.74 for regular nodes, and the R^2 values for $n = 1$ were 0.75, 0.74 and 0.55 respectively. The first values represent a positive linear relation between the story size and the number of focal nodes inside the story generator, the second values represent a negative linear relation between the story size and the number of isolated nodes, and the third values represent a negative linear relation between the number of impasses and the number of regular nodes.

Figure 17: Story size averages versus percentages of focal and isolated nodes, and impasse averages versus percentages of regular nodes

Discussion

The main goal of this project was to identify how the knowledge structures of an automatic generator of narratives influence the presence of diverse features of its generated stories.

In table 1, we present a summary of the linear relations found between the story-characteristics and the structural-characteristics described on this paper. These results are divided into two sections: node relations and cluster relations.

Element	Positive relations	Negative relations
Focal nodes	novelty, climax story size character threads E-R ratio	
Regular nodes		impasses
Isolated nodes		novelty, climax story size character threads E-R ratio
City clusters	opening	closure soc. resolutions
Town clusters		originality
Island clusters	originality closure soc. resolutions	opening

Table 1: Summary of the obtained relations

We utilized as story-characteristics opening, climax, closure, originality, novel contextual structures, impasses, E-R ratio, story size, character threads and social resolutions, in grounds of a previous work on evaluation of stories to determine its interestingness, novelty and coherence (Pérez y Pérez 2014), features considered relevant for a story to be considered creative.

We made use as structural-characteristics the percentage of nodes and clusters inside the knowledge base of the analyzed agents. Nodes represent CSs obtained after interpreting the previous stories of the agents, and clusters represent groups of similar nodes. We defined the concept of similarity between nodes in terms of the similarity between the relations of the CS-contexts. Representing the internal knowledge of an agent as CSs let us qualitatively describe it, which lead into the creation of structures, called C-maps, to visualize the similarities among its information.

Our findings let us now formulate questions about the process of incorporating new stories into the agent's knowledge base. Before this research, we envisioned to have an agent with as many previous stories as possible, but know we have evidence that this is not always the best scenario. For instance, this agent would be a deficient evaluator since its evaluations, in particular for novel CSs and originality, will often be low. This assumption lead us to redefine our definition of novelty. Now, we perceive diverse scenarios where novel CSs emerge: when a new story originates different context from those in the evaluating agent; when a new story utilizes the existing contexts but in different ways; when a new story utilizes rare contexts. With the categorization presented for nodes and clusters, we are able to identify these new context types, to measure its presence, and to validate how it affects the story generation process.

These results lead us to think on the optimal number of previous stories that an agent should have to generate higher-evaluated stories, and to become an accurate story evaluator. If an agent had enough stories to cover all the possible story-contexts, its evaluations of novelty and originality will always be zero, and the number of possible continuations for every story would be so vast that unusual and even incoherent stories could be generated. Its C-map would consist of focal nodes galore, and a big city-cluster. In general, as we develop a better understanding of the implications of diverse knowledge arrangements for the story generation process, we will be able to progress in the construction of more accurate ways of generation and evaluation of such outputs.

It is worth to mention that our final averages does not consider all the 90 stories generated by every agent, since some of these outputs lacked of what we considered as basic characteristics to be considered stories (a minimal number of actions, preconditions satisfied and one character thread). We also measured the ratio of these valid stories against the invalid stories and we looked up for relations with our structural metrics, but we did not find any linear relation. These results give us an inkling of the complexity of generating valid stories. In further research, we will look for non-linear relations and multifactorial relations to cast light on which structures might diminish the generation of invalid stories.

In grounds of our presented results, we showed that, in general, focal nodes improve the novelty of the generated stories because of its conception process. These nodes are built from similar inspiring stories when their CS are extracted and incorporated to the repository. In fact, these nodes provide a wide variety of continuations for a single context since every connection to a focal node comes from a similar CS that can be employed to progress a new story. Moreover, the size of the generated stories is bigger when focal nodes come into play because of this higher number of possibilities, and becomes easier to reach an appropriate number of tensions during the story climax, and to maintain a unique character thread. On top of that, the number of $actions_E$ increases, and is closer to the number of $actions_R$, resulting in a higher E-R ratio.

We also found that, in general, isolated nodes play the opposite role of focal nodes. For instance, they diminish the novelty, climax and the size of the generated stories. Nevertheless, an isolated node can be perceived as a focal node in an early developmental stage, so they are required for the focal nodes to come into play.

Regarding to clusters, cities provide a solid ground for the stories to initiate, but as the process continues, cities widen the number of possible continuations and the stories tend to have closures with multiple unsolved tensions. Contrasting with our initial assumptions, we did not find any evidence of a strong negative relation between cities and originality nor a strong positive relation between them and valid stories.

On the other hand, the presence of islands in the early stages of a story originates multiple impasses, but they incorporate original paths and bounded closures. Finally, towns diminish the originality of the stories since they provide solid structures with multiple similar contexts, but they still lack of focal nodes so the continuations are still not too different.

These results support our claim about the existence of linear relations between structural elements in the knowledge base of our storyteller and features of its generated stories. In our model, these elements are obtained from a set of previous stories, which shows how previous experiences affect the generation of new narratives. Nevertheless, we still need to do additional research efforts to validate if the obtained relations are causal (i.e. the structural-characteristics are the origin of the story-characteristics), or circumstantial (i.e. the structural and the story characteristics are both generated by additional factors). This research has widened our scope to identify the existence of these additional factors, to progress in our understanding of how the structural elements inside the knowledge base of any agent affects the characteristics of its generated narratives.

Conclusions

We showed in this paper relations among structural settings of the knowledge base of an automatic storyteller (Mexica) and features of its generated stories.

We introduced the concept of nodes and clusters built upon CSs inside the agents' knowledge bases. We classified nodes into three different categories: focal, regular and isolated, and also classified clusters of these nodes into three different sets: cities, towns and islands. We have described connectivity maps (C-maps), which reflect how similar the nodes inside the knowledge base of a storyteller are.

We described a set of metrics to identify story features such as preconditions fulfilled, novel contextual structures, opening, climax, closure, character threads, social resolutions, originality, E-R ratio, and number of impasses, and a set of metrics to describe knowledge structures inside the agents based on the nodes and clusters they contain.

We hypothesized how nodes and clusters, when present in the knowledge structure of an automatic storyteller, affect diverse story features. Next, we validated these claims by implementing our model utilizing Mexica and Social Mexica, evaluating each of the generated stories, and then contrasted the evaluations against each of the metrics describing the internal structure of the knowledge bases utilized during the generation process.

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Emergence of eye–hand coordination as a creative process in an artificial developmental agent

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Abstract

Based on Piaget's theory of cognitive development and an extension of the Engagement-Reflection model of creativity, the *Developmental Engagement-Reflection* (Dev E-R) model characterizes the early cognitive development of an agent as a creative activity. In its first version, Dev E-R uses an agent that can see and move its head; through interactions with its environment, it is able to develop elaborated behaviors consistent with Piaget's ideas. This work describes an advancement of our model. We give our agent a hand (tactile sensor) so it can detect the presence and features of an object in its environment; we also study the necessary mechanisms to coordinate its vision with the sense of touch. We report the behavior of the agent when it is granted the capacity of touching without seeing (i.e. the agent was "blind") and when both skills, touch and sight, come together. For such purpose, we place an agent in a virtual environment and let it perform in different contexts. We analyze how new knowledge structures results from prior experiences and interactions with the environment. The outcomes from the experiments reveal that it learns new skills associated with eye–hand coordination. We observe that the arising developmental behavior resembles some of the features reported by Jean Piaget.

Keywords

Developmental robotics, creative behavior, Piaget, engagement-reflection, Dev E-R, eye–hand coordination

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1. Introduction

Cognitive development is a fascinating subject that is taking the attention of many researchers in areas like developmental approaches to artificial intelligence (AI), cognitive science, philosophy, and so on (e.g. Asada et al., 2009; Guerin, 2011a; Lungarella, Mettay, Pfeiferz, & Sandiniy, 2003; Weng et al., 2001). One of its main goals is to study agents' capability of adaptation to its (sometimes changing) environment. Adaptation is seen by many academics as a necessary condition for creative behavior (e.g. Cohen, 1989; Gorney, 2007; Runco, 2007). Piaget (1936/1952) characterizes adaptation as a mechanism comprised by two processes called assimilation and accommodation: Assimilation allows children to face new situations by using their knowledge from past experiences; accommodation allows dealing with new situations by progressively modifying their expertise in order to incorporate the results of their new experiences. Clearly, these three concepts—cognitive development, adaptation, and creative behavior—are closely related to each other. We use them as a base for our research. The *Developmental Engagement-Reflection* (Dev E-R) model represents the early cognitive development of an agent as a creative activity (Aguilar & Pérez y Pérez, 2015). Dev E-R characterizes some of the aspects that take place during the sensorimotor period described by Piaget (1936/1952). The model uses an extended version of the computational model of creativity known as Engagement-Reflection (Pérez y Pérez, 2007; Pérez y

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Pérez & Sharples, 2001, 2004) to represent Piaget's assimilation-accommodation adaptation process. To our knowledge, this is the first computational system that addresses cognitive development as a creative process. It proposes three characteristics for the construction of developmental agents: (1) a hedonic intrinsic motivation system based on the recovery and preservation of pleasant stimuli; (2) a knowledge representation based on affective responses, emotional reactions, and motivations; and (3) a learning mechanism driven by surprise and cognitive curiosity, based on generalization and differentiation of schemas, and on using its knowledge of past experiences to deal with new similar, but not identical, situations.

In Aguilar and Pérez y Pérez (2015), we reported the behaviors learned by the agent when it was granted with the capability of seeing its world (a living room with furniture, plants, and some toys). This article complements that work. Here, we present an advancement of Dev E-R where we incorporate a hand that allows the agent to touch its environment. Our main interest is to study which new behaviors arise as a result of adding this new sensory ability. Because, as far as we know, there are no other developmental agents that employ the Engagement-Reflection Model, we consider necessary to study further the limitations and scopes of our model. In this article, we have the hypothesis that if Dev E-R provides the bases for a framework flexible enough for implementing a developmental agent, the incorporation of new senses (such as the sense of touch) should be possible without modifying the core of the current knowledge structures and internal processes. That is, the same model must provide the necessary infrastructure to develop new abilities. These are the questions that drive this research: What modifications does Dev E-R require in order to add the sense of touch? How can the sense of touch and sense of sight be coordinated within our model? Given these new features, what new abilities will our agent develop? Our results suggest that the new skills developed by the agent resemble what Piaget describes as the first behaviors associated with hand and the first sight–touch coordination seen in newborns from ages 0 to 4 months. In this way, the inclusion of the sight–touch coordination seems to produce in our model a more elaborated cognitive development. Furthermore, this result suggests that it is possible to include new senses to our agent without substantial modifications of the model. Nevertheless, it is necessary to assess deeply the flexibility of our approach.

This article is structured as follows: section 2 presents a summary of related work; section 3 contains a description of the developmental agent and the Dev E-R model; section 4 explains the changes needed to give the sense of touch to the agent; section 5 describes the experiments we performed to test our model as well as the results obtained; in section 6, we discuss the behaviors learned by the agent in the context of Piaget's theory, its developmental path, an evaluation of its development as a creative process, and a comparison with other methods; finally, in section 7, we present the conclusions.

2. Related work

Probably, Alan Turing (1950) is the first person to conceive the idea of developing a program that simulates an artificial baby which could be later educated like a child until it gets an adult level. Around the same time (1920s–1970s), Jean Piaget, an epistemologist, psychologist, and biologist, publishes important research papers related to the development of intelligence from infants to adults, which are still a reference to anyone interested in cognitive development (see, for example, Piaget, 1924, 1936/1952, 1954, 1985). Two decades later, during the 1960s and 1970s, Papert (1963) and Boden (1978) suggest that AI and Piaget's theory of cognitive development can be highly useful from each other.

It is until the beginning of the 1990s, that under the influence of the idea of embodiment (which states that intelligent behavior can only come from the interaction between the mind, the body, and the environment), a new area of research named as *developmental robotics* (sometimes also called *epigenetic robotics*) arose. Its focus of interest is in the intersection between robotics and developmental sciences. A review of this emerging area can be found in Asada et al. (2009); Lungarella et al. (2003); Elliott and Shadbolt (2003); Metta, Sandini, Natale, and Panerai (2001); Asada, MacDorman, Ishiguro, and Kuniyoshi (2001); Weng et al. (2001); and Sandini, Metta, and Konczak (1997).

From that decade to the present, different computational models that simulate some aspects of early cognitive development, from Piaget's perspective, have appeared. Guerin (2011a) and Stojanov (2009) present a review of these kinds of works. However, none of these systems consider the relation between cognitive development and creativity. In 2013, such relationship was discussed during the Association for the Advancement of Artificial Intelligence (AAAI) Spring Symposium called "Creativity and Cognitive Development." The discussion was around the hypothesis that the same mechanisms involved in the generation of creative artifacts are observed during cognitive development, in particular during the constant reconceptualization of one's understanding of the environment. In a paper presented in that symposium, Sandra Bruno (2013) suggests that creativity is what enables adaptation, and that in the very early stages of development, one of the first creative attitudes involves the transformation of reflexes into schema. In Stojanov and Indurkhya (2013), the authors reflect about how research in developmental AI and robotics remains completely disconnected from computational creativity, and propose to see the process of analogy as one of the common mechanisms present in both fields, as well as the consequences of this point of view. In the same line of thought, Bickhard (2013) presents a discussion about the creativity of development and the development of creativity. On one hand, he states that "development is inherently a matter of an evolutionary epistemology, and, thus, inherently involves creative construction processes in the face of new situations and problems," and on the other hand, he discusses the different aspects of an internal evolutionary epistemology that can contribute to creativity. Other related works that were presented in this symposium include Miller (2013) and Indurkhya (2013). Nevertheless, except for our work (Aguilar & Pérez y Pérez, 2013), no other computer system that models early cognitive development as a creative activity was presented. We believe that this is an important relationship that needs to be further studied, and we refer to it as development of early-creative-behavior.

3. The developmental agent and the Dev E-R model

This section provides a summary of our model introduced in Aguilar and Pérez y Pérez (2015).

The developmental agent is named Jacques, after Jacqueline, one of the daughters of Jean Piaget, who was an object of study and inspiration for him. Jacques interacts with a three-dimensional (3D) virtual world containing simple 3D models of typical objects that may be found in real life. Such objects have the following characteristics: luminous or non-luminous, static or moving, color, and size. The agent uses a virtual camera (set in its right eye) with a field of vision of 60° to visually sense the world. The images taken are internally represented as a $180 \times 120 \times 3$ matrix. Its field of view is divided into nine different areas. It has the capability of moving its head 10° to the right, left, up, down, up-right, down-right, up-left, and down-left. These are the physical actions, or external actions, that the agent can perform.

The general perception-action cycle that Jacques implements is summarized in Figure 1.

3.1. *Motivational system*

The agent simulates affective responses, emotional reactions, and motivations that push it to act. These are inspired by Piaget's ideas, associated with the relation between affectivity and development of intelligence (Piaget, 1981). The first responses consist of intensity and valence, represented by the agent through variables that span along a scale of –1, + 1, + 2, wherein –1 represents disliking and + 1/ + 2 represent 2 degrees of liking. The rest are represented internally as Boolean variables having a true value when the agent presents such emotional reactions or motivations. The situations under which these are triggered are listed in Table 1.

3.2. *Knowledge representation*

The agent has a memory wherein it stores all its knowledge. Particularly, the agent saves in this memory its current perception of the world (represented through the *Current-Context* structure) and actions to interact with its environment (represented through schemas).

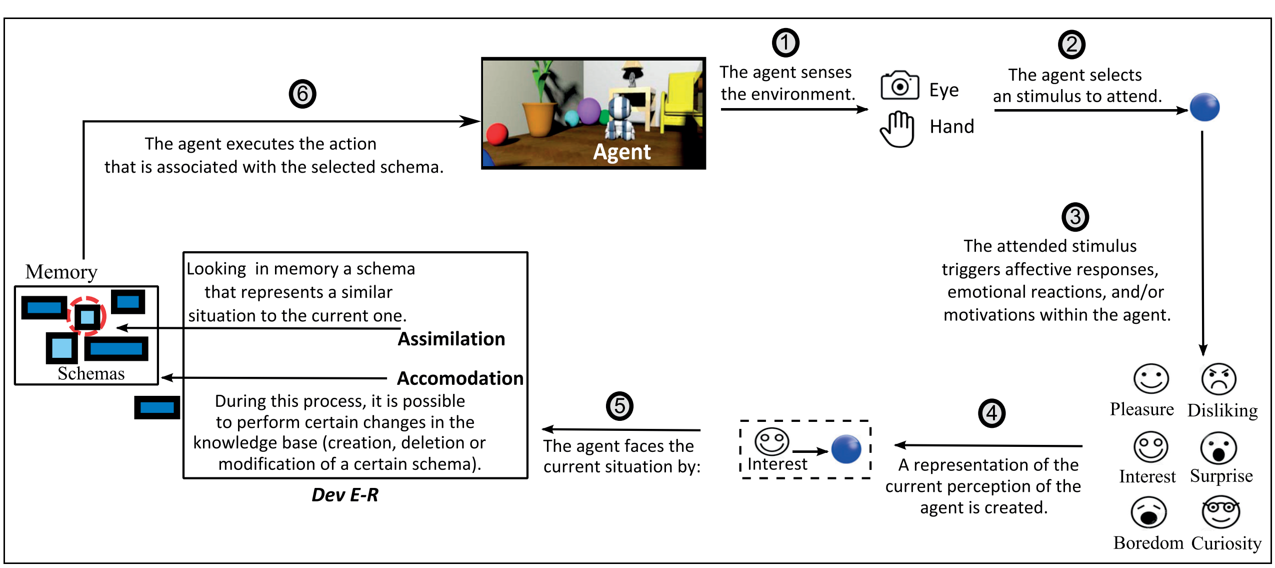

Figure 1. The perception-action cycle used in Dev E-R.

Table 1. Summary of the situations under which the different affective responses, emotional reactions, and motivations are triggered.

Name	Description
Affective responses	
Pleasure	It is triggered when the agent pays attention to a bright spot. It can assume three values: + 2 when the agent pays attention to a bright blob that it sees in the center of its visual field, + 1 when the element is seen in its peripheral area, and –1 when the agent loses a stimulus it likes, that is when the attended item disappears from its visual field. In other words, the –1 value is equivalent to disliking.
Emotional reactions	
Interest	Triggered as a result of executing an internal action named *show_interest_in A*, where *A* can be any stimuli (visual or tactile).
Surprise	Triggered when the agent "accidentally" recovers an object it likes, and when the current situation is faced by using agent's experience from a similar, but not identical, situation, and even then the expectations are met.
Boredom	Triggered when the agent attends, in a consecutive sequence, the same object a number of times.
Motivations	
Cognitive curiosity	Triggered when the expectations of the agent are not met.

3.2.1. Current-Context. The *Current-Context* is a structure composed by two parts: (1) the *Current-Visual-Context*, and (2) the agent's current expectations, which are defined as an *Expected Current-Visual-Context* (explained later in this section). The *Current-Visual-Context* is composed by two parts: (1) the features of the object that is in the center of attention of the agent (its color, size, movement, and position within the visual field); and (2) the affective responses, emotional reactions, and motivations triggered in the agent by such object. This way, the agent is able to represent its present perception of the world in terms of what the object(s) at the center of its attention (described through their features) are provoking in it, that is, whether they are causing a feeling of liking, disliking, interest, boredom, surprise, cognitive curiosity, and/or any expectation. Figure 2(a) shows an example of a *Current-Context*. With the purpose of providing a simpler, more compact notation, henceforth, current contexts composed solely by affective responses are herein represented in the form of Figure 2(b).

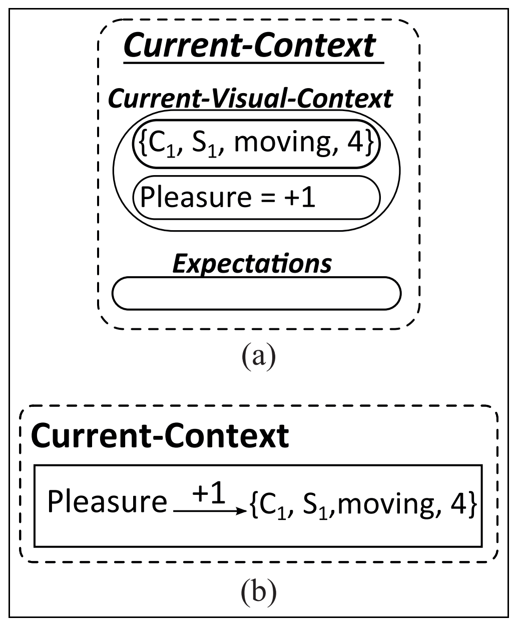

Figure 2. (a) An example of a *Current-Context* structure, which represents that the agent is seeing a pleasant object, which consists of a ball of C_1 color, and size S_1, which is moving within position 4 of the visual field; and (b) the same *Current-Context* using the alternative notation.

3.2.2. Schemas. Schemas as used herein are knowledge structures simulating the sensory-motor schemas described by Piaget. There are two types: basic and developed.

Basic schemas represent innate behaviors and tendencies observed by Piaget in babies, which are present in the agent from its initialization. These are represented as contexts associated to actions. The contexts used in the schemas are structures similar to the *Current-Context* structure. As opposed to the *Current-Context* structure, the contexts of the schemas may define the features of the object in terms of non-instantiated variables. As an example of the foregoing, Figure 3(a) shows an illustration of a basic schema, which associates the situation of feeling disliking, triggered by an object of any color = a, of any size = b, with any movement status = c, and in any position within the visual field = d, with the action of performing a random external action (e.g. a movement of the head to the right). Henceforth, small letters shall represent non-instantiated variables. When the n features describing the object in a context are non-instantiated variables, it is said that the structure to which it is associated is an abstract schema of type T_n (as the schema shown in Figure 3(a), which is type T_4). On the contrary, if all features are instantiated variables, we have

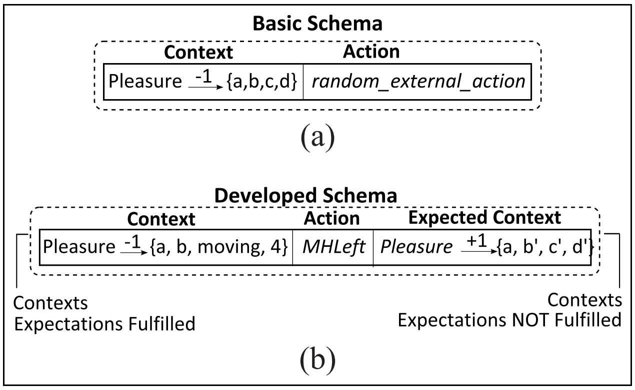

Figure 3. An example of a (a) basic schema and (b) developed schema.

a concrete schema of type T_0. Similarly, there are intermediate schemas, types $T_1, T_2, \ldots, T_{n-1}$, with several features in terms of non-instance variables. The concept of type is important for the implementation of the accommodation process, which is based on generalizations (modifying a schema so that it becomes more abstract, for example, changing it from T_2 to T_4) and in differentiations (modifying a schema so that it becomes more particular, for example, changing it from T_3 to T_1). These processes are described in section 3.3.2.

Developed schemas are constructed based on the interactions of the agent with its environment (explained later in this section) and represent new behaviors. These are composed by a context, an action to be executed, an expected context, and a set of contexts with which the expectations have been fulfilled (named "Contexts Expectations Fulfilled") and others that were not fulfilled (termed "Contexts Expectations NOT Fulfilled"). Figure 3(b) shows an example of a developed schema, which associates the disliking situation triggered by a moving object of any color, any size, in position 4 within the visual field of the agent, with the action of moving the head left, and the expectation of recovering the affective response of pleasure toward that same object (two objects are considered the same if both have the same color). This is an example of a T_2 schema, as two of the features of the context (without considering the ones used in the expected context) are in terms of non-instantiated variables.

The term *visual schema* is used to define the structures whose context refers only to visual objects.

3.3. Adaptation and learning mechanisms

The adaptation and learning mechanisms are in charge of using and constructing the knowledge of the agent (represented as sensory-motor schemas).

3.3.1. General functioning. The Dev E-R model, in *Engagement* mode, searches its memory to find all schemas whose contexts represent a similar situation to the one described in the *Current-Context*. If during this process the agent is found to know more than one way to act given the current situation, then one of those ways is preferred. The selection is performed in such a way that the developed schemas are assigned a higher probability of being chosen over the basic ones, and from the developed schemas, the one resulting in the highest number of expectations fulfilled and expected to result in the most pleasure is the one that will most likely be picked out. The final decision is made on a random basis, which considers the above information.

For instance, let us suppose that the current context of the agent is the one shown in Figure 2, and that during Engagement, the agent found three possible schemas to match: (1) a basic schema with an action where the agent continues showing interest in the moving ball; (2) a developed schema with an action where the agent moves its head to the left; with that movement, it expects to increase its pleasure with a probability p_2 (such a probability depends on its experience); (3) a developed schema, similar to the second one, with the associated action of moving the head to the left and up; it expects to increase the pleasure with a probability p_3, where $p_2 > p_3$. The system selects at random which schema to match; however, because $p_2 > p_3$, the second structure has a higher probability to be chosen than the third one; because the agent prefers to match developed schemas rather than basic schemas, the first option in this example has the lower possibility to be used. In this way, given the same situation and the same memory state, most of the time the agent will move its head toward the left; in some other occasions, it will move its head toward the left and up; and occasionally, it will show interest toward the ball. Therefore, under equal conditions, the agent will not always behave in the same way. The simulation is non-deterministic; it depends on the knowledge that the agent has accumulated in memory.

When a schema is selected, its associated action is executed; in case the designated structure is a developed schema, then the expectations are registered in the *Current-Context*. The agent senses once more its world, updating the structure of the *Current-Context*, and the cycle continues. When no schema may be matched in the memory, that is, when the agent faces an unknown situation, then an impasse is declared. In this event, an adaptation process is required, whether by assimilation or by accommodation. These processes may be performed automatically or analytically, for instance, through an analogic reasoning. However, when the agent initiates the execution, it lacks reflexive skills to help it deal with such type of situations (based on the early substages that are being modeled). Consequently, adaptation in this implementation is simulated as an automatic activity that is being performed in *Engagement* mode.

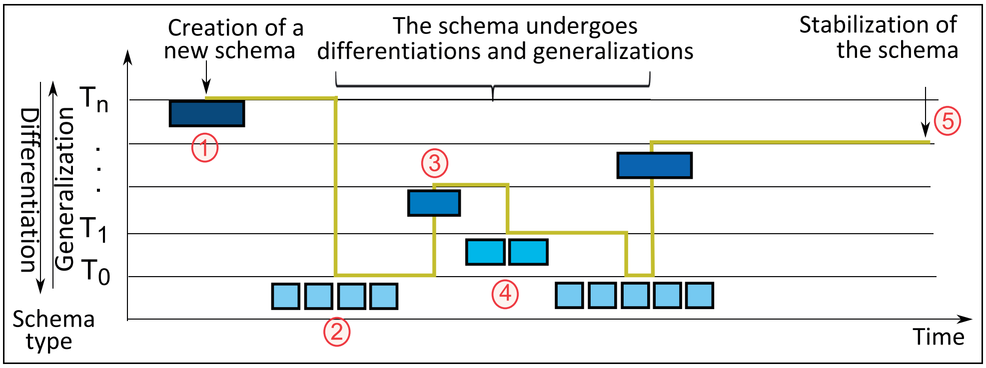

Figure 4. Summary of the accommodation processes of the agent's schemas: (1) A new T_n-type schema is formed when the agent presents an emotional reaction of surprise, that is, when it accidentally recovers an object of its interest. (2) The schema is differentiated in particular structures, type T_0, when its associated expectations are not fulfilled in a determined percentage of times. (3) It is generalized into a schema type T_{n1} ... T_1 when it is detected that one same action may lead to recovering several objects with different features. (4) If the schema continues to lead the agent to enter a conflictive cognitive state, then it is considered to be still very general and is thus differentiated once more into particular schemas. (5) This process continues until the schema is deleted or until accommodations stop because the expectations are fulfilled most of the times, that is, until it becomes stabilized.

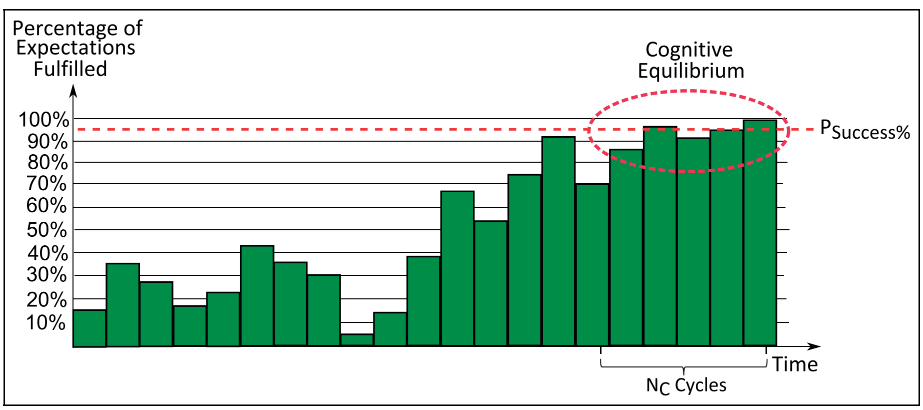

Figure 5. A depiction of the moment when the agent enters a cognitive equilibrium state. When the agent initializes and begins to create its own schemas, its expectations are fulfilled in a very low percentage of times, resulting in the necessity of accommodating its knowledge. In time, the agent is capable of interacting with its world without the need to further modify its knowledge, as the expectations were fulfilled most of the times (at least in $P_{Success}$% of the times, during the last N_C cycles). At this time, the agent is said to have entered a state of cognitive equilibrium.

3.3.2. Simulation of the accommodation process. Accommodation, as understood under Piaget's theory, refers to the process through which the child modifies an existing schema or creates an entirely new one to deal with an unknown object or event (Ormrod, 2012). Inspired by this concept, in the Dev E-R model, the knowledge structures are gradually created and modified by means of the generalization and differentiation processes summarized in Figure 4.

An important aspect to highlight is that at some point in time, agent's memory contains schemas of various types that may involve different senses. For a detailed explanation of the accommodation process, see Aguilar and Pérez y Pérez (2015).

3.3.3. Simulation of the cognitive equilibration process. The accommodation process continues until the moment arrives when the agent can interact with its world during the last N_C cycles without detecting the need to modify its knowledge, as the expectations were fulfilled most of the times (at least in $P_{Success}$% of the times), as depicted in Figure 5. At that moment, we can say that the agent has entered a state of cognitive equilibrium, and the schemas that have been built by the agent up to that point are considered stabilized.

If any schema is built, deleted, or modified again, then the agent is considered to have entered again in a state of cognitive disequilibrium. Consequently, it will have to meet again the condition stating that the need to modify its knowledge was not detected in the last N_C cycles, as the expectations were fulfilled most of the times, and so a state of cognitive equilibrium is achieved again.

Each time the agent enters a state of cognitive equilibrium, its capability of finding partial matches between its *Current-Context* and its basic schemas and those developed schemas that have been stabilized is activated, as described in further detail in the following section. At the beginning, the agent was not able to perform such skill.

3.3.4. Simulation of the assimilation process. Assimilation refers to the process of responding to new facts and situations according to what is already known and recoverable from the memory (Guerin, 2011b). This process is modeled in Dev E-R by seeking schemas representing situations which are similar to the one described in the *Current-Context*.

At the beginning of the execution, a 100% match must be found between both structures. However, once stabilized schemas begin to appear on the agent's knowledge base, it begins to allow partial matches, which may be presented in two ways. First, if the *Current-Context* consists of a single affective response, then any of the elements thereof is allowed to differ from any of the elements of the context associated with a schema (the type, valence, or intensity of the affective response, or in the properties of the object—color, size, movement status, or position within the visual field). Second, if the *Current-Context* consists of more than a single affective response, then each of the latter is allowed to match a different schema, or even one of said responses may be allowed to not have a match. It is important to stress that partial matches are performed only in basic schemas, as well as in developed schemas which are already considered stable.

Sometimes, assimilation leads to accommodation. For example, in cases where the agent (1) faces a current situation by performing a partial match between such situation and any of the developed schemas and (2) after applying the associated action, the expectations of the agent are fulfilled. Under such circumstances, an emotional reaction of surprise is triggered, leading to the construction of a new schema representing the way in which the agent successfully faced the new situation. With the creation of new schemas, the knowledge base of the agent suffers further accommodations, leading to a new state of cognitive disequilibrium. The agent remains at this stage until the new schemas are stabilized. At that moment, the agent enters again into a state of cognitive equilibrium. The new stabilized schemas begin to be used in finding partial matches, thus leading to the creation of new schemas and causing the agent to enter once again into a state of cognitive disequilibrium, and so on. This is how the agent simulates the process of cognitive development, going from a state of disequilibrium to a state of equilibrium, and again to disequilibrium, and so on.

4. Adding the sense of touch to the agent

To give the sense of touch to the agent, five main changes are needed:

1. Create a simulated tactile sensor that can detect (1) the presence of an object in contact with the palm of the hand (the agent can only touch one element at a time) and (2) its texture. Regarding the latter, it is possible to achieve an implementation which enables the agent to increase its ability to differentiate various tactile properties prevalent on the surface of the elements in the surroundings (see, for example, Jamali, Byrnes-Preston, Salleh, & Sammut, 2009). These may include, for instance, several degrees of roughness. This may be carried out analogous to vision (see Aguilar & Pérez y Pérez, 2015). Thus, at the beginning, the agent would only be able to differentiate between very smooth and very rough. In time, through the interaction with the virtual world, the agent would be able to differentiate several degrees of roughness. However, for simplicity purposes, in this article, we are assuming that the agent has learned to recognize a number of textures, which have been labeled as "t_1," "t_2," "t_3," and so on.
2. Add a tactile texture to each object in the environment (in this implementation, this is done by assigning them a label such as "t_1").
3. Update the motivation system in such a way that (1) an affective response of pleasure with intensity $+1$ is triggered when the agent has selected a tactile stimuli as its center of attention; and (2) an affective response of pleasure with intensity –1 (i.e. displeasure) is triggered when the agent loses a tactile stimulus it likes, for example, when it drops the attended object.
4. Change the *Current-Context* structure to include a new component named *Current-Tactile-Context* which is analogous to the *Current-Visual-Context*. This structure corresponds to an internal representation of what the agent is touching. The schemas with only tactile information are named *tactile schemas*.
5. Modify the attention module in such a way that when the agent is detected to have been in cognitive equilibrium for N_C cycles, and its knowledge base contains stabilized visual and tactile schemas, then the agent becomes capable of representing both visual and tactile data in its current contexts. In other words, the agent becomes capable of paying attention to what it sees and what it touches simultaneously. The term *tactile-visual schema* is used to describe those schemas referring to visual and tactile stimuli.

5. Experiments and results

We present in Aguilar and Pérez y Pérez (2015) the results obtained when the agent is granted with the ability to see but not touch the world around it. Said results are summarized herein below because these are used for the subsequent experiments. For this article, we are interested in finding what new behaviors arise when the agent is granted the ability to touch. For this purpose, two new sets of experiments were designed. The first one consists in configuring the agent so that it could only touch but not see its world. The second one involves granting the agent both abilities: seeing and touching its environment. The description of said experiments, along with the results obtained, is reported herein below.

5.1. First set of experiments: the agent can only see its world

The first set of experiments involved letting the agent interact in three separate executions within the living room shown in Figure 6. This environment contained 3D models of pieces of furniture, plants, toys, and so on. All the objects were static, except for five balls of different colors, which began to move at different times and in different predefined directions (sometimes they rolled from left to right, and back; other times, they bounced). In these experiments, the agent was initialized with the first two schemas shown in Figure 7, which represent “innate” tendencies described by Piaget (1936/1952). The first innate conduct allowed the agent to keep its attention focused on the objects of its interest; the second one permitted the agent to perform an attempt at recovering such objects whenever they disappear. Jacques finished its execution (in one of the runs, after having remained in a state of cognitive equilibrium during the last 1000 cycles) with 29 new schemas in total (13 to recover objects it lost in the different positions within the visual field, 8 to keep those that were moving, and 8 to preserve those that were static).

When the agent used jointly the schemas it had developed, we noticed that it learned the following behaviors (listed herein in the same order in which they were constructed): (1) recovering back in its visual field the elements of agent’s interest which came out of said field, (2) following visually pleasant objects, (3) centering within the visual field the elements which were of agent’s interest and which were moving, and (4) centering in the visual field the elements that were interesting for the agent and which were static.

5.2. Second set of experiments: the agent can only touch its world

The second set of experiments consisted in configuring the agent so that it could only touch but not see its world. Its development was considered completed when it remained in a state of cognitive equilibrium during the last 250 cycles, that is, until the agent showed to have acquired new skills that enabled it to interact with the environment (recovering and preserving the tactile objects that were pleasant for the agent), using the

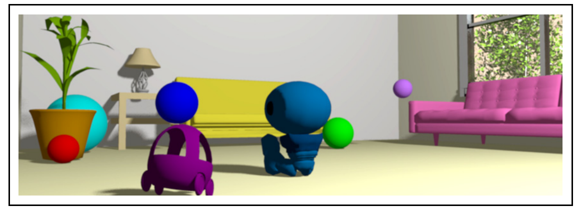

Figure 6. Image of the environment with which the agent interacted during the experiments.

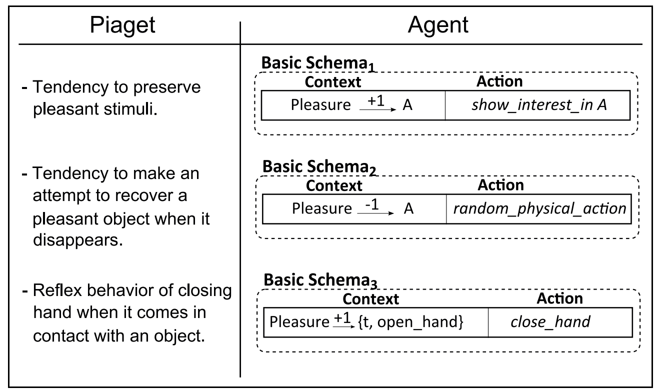

Figure 7. Basic schemas with which the agent was initialized. These schemas represent the predefined behaviors that were known initially by the agent to interact with its world.

knowledge that it had built. The reason why we selected 250 cycles is because empirically we realized that the tactile skills that it acquires in this setup are faster to learn than the ones when it could only see. Thus, if we had used 1000 cycles as in the previous experiment, the only consequence would have been that it would take longer to finish its development. However, if we had used a smaller value than 250, there is a risk of a premature stabilization of the schemas causing the agent to be unable of predicting the consequences of its actions with an adequate precision.

Dev E-R is a research tool; therefore, the user can modify a set of parameters that influence the behavior of the agent (see Table 2). We performed several tests to study the consequences of altering their values. The following lines provide a summary of what we found out. When the first four parameters in Table 2 were set to high values, the agent took longer to develop all its schemas; so, we prefer to use low values. The parameter $P_{FailureT4}$ shapes the time that the agent spends trying to recover lost objects by using the same action that previously worked well. We observed that choosing a low percentage such as 10% is a good compromise between giving the schema time to gain knowledge about the consequences of its associated action and allowing the agent to try different actions to recover pleasant stimuli. Parameters $P_{DeleteT0}$, $P_{DeleteT4}$, and $P_{DeleteT3T2}$ affect the decision of which schemas should be deleted because

Table 2. Values and descriptions of the main Dev E-R model parameters used in the second set of experiments.

Parameter name	Description	Value
N_{UsedT4}	Minimum number of times a schema type T_4 had to be used before it could be accommodated.	4
N_{Trials}	Minimum number of times an object must be assimilated into a schema so that it is considered in the differentiation process.	2
N_{T0}	Necessary number of schemas type T_0 in order to be able to perform a generalization.	2
N_{UsedT0}	Minimum number of objects assimilated into a schema type T_0 required to delete it.	6
$P_{FailureT4}$	Minimum percentage of failure by a schema type T_4 in order to consider its accommodation.	10%
$P_{DeleteT0}$	Minimum percentage of failures needed to delete a schema type T_0.	50%
$P_{DeleteT4}$	Minimum percentage of failure to delete a schema type T_4.	90%
$P_{DeleteT3T2}$	Minimum percentage of failure by the schema types T_3 and T_2 so they can be deleted.	85%
$P_{SuccessObj}$	Minimum percentage of success to recover the same object so that it can be considered into the differentiation process.	60%

Dev E-R: Developmental Engagement-Reflection.

they are not good enough predicting the consequences of their associated actions. For instance, $P_{DeleteT0}$ is linked to schema type T_0. Because these types of schemas connect actions to very specific stimuli, a failure rate greater than 50% indicates a bad accuracy of the prediction. On the contrary, $P_{DeleteT4}$ and $P_{DeleteT3T2}$ are linked to schemas that continuously are generalized and differentiated. As a result, their set of fulfilled and not fulfilled expectations is constantly changing. Thus, such schemas should only be deleted when the experience registered in them mainly represents failure cases; otherwise, valuable experience may be lost. To achieve this behavior, it is necessary to set the parameters with high values. Finally, the last parameter is related to the flexibility of the agent to deal with indeterminacy of the consequences of the agent's actions. The lower it is set, the more flexible it is. For example, if every time the agent moves its head, the attended object changes to a contiguous area of its field of vision, then a value of 100% could be used. Based on the previous observations, we initialized our agent with the parameters shown in Table 2 to perform our experiments.

The agent was also initialized with the following initial knowledge.

5.2.1. Initial knowledge. The agent was initialized with the three basic schemas shown in Figure 7. These represent the only initial behaviors that were known by the agent to interact with its world. The third one modeled the reflex behavior of closing the hand when a pleasant element comes into contact with it. Variable A represented any tangible object defined as $A = \{\text{texture}, \textit{hand\_status}\}$, wherein said hand status may have either of these values: *closed_hand* or *open_hand.*

Finally, the only physical (external) actions that the agent may perform were those associated with the movement of its hand (up, down, right, left, front, back, closed, and open).

5.2.2. Virtual world setup. In this set of experiments, the agent interacted again in three separate executions within the living room of the house shown in Figure 6. In these executions, all the objects were static, except for the five balls that were moving as follows:

- When the agent had its hand open and not in contact with any object, sometimes the system randomly picked any of the five balls and placed it in its hand (so that its touch sensor could detect it during the next cycle).
- When the touch sensor was in contact with any object and the agent executed the action *close_hand*, then it was considered that the object had been grasped.
- The grasped objects moved accordingly to hand movements.
- By default, after n cycles (for this experiment, $n = 1$), the agent would automatically open its hand (unless when, during the current cycle, the action *close_hand* had been selected).
- Upon the hand being opened, the object that had been grasped could (1) remain in the same position and continue in contact with the touch sensor or (2) go back to its initial position. The selection of (1) or (2) above was made by the system on a random basis.

Regarding the tactile features that the agent could recognize on the objects it touched, this experiment was initialized with the capacity of recognizing five different textures (labeled "t_1," "t_2," "t_3," "t_4," and "t_5"), one for each ball.

The three executions began with the agent sitting in the middle of the environment with its hand open in front of it, and five balls in positions that were out of the agent's reach. The results obtained are reported herein below.

5.2.3. Results. We should point out that, just like in the first set of experiments, the new skills acquired by the agent were based on learning how to preserve affective responses of pleasure triggered by the objects of the

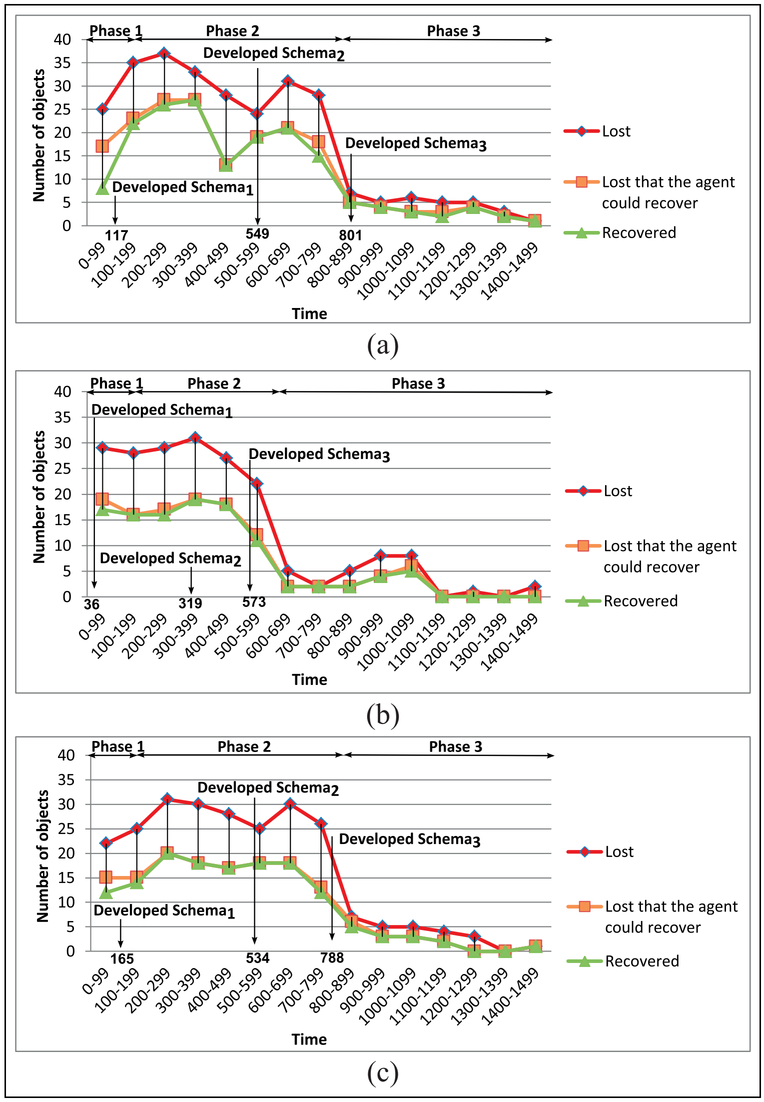

Figure 8. These graphs show the evolution of the number of pleasant objects lost by the agent, in contrast to the number of objects that the agent could recover, in each of the three executions: (a) execution 1, (b) execution 2, and (c) execution 3.

agent's interest and learning to recover them when they disappear. With this in mind, in the graphs of Figure 8, in groups of 100 cycles, the following is presented: (1) the number of pleasant objects lost by the agent, that is, which it had grasped but were lost when opening the hand (shown in red diamonds); (2) the number of objects lost that the agent could recover, as upon release by the hand, the system chose to leave them in contact with its hand (shown in orange squares); and (3) the number of objects that the agent was able to recover successfully (in green triangles). Three phases may be identified in these graphs:

1. *Phase 1* includes approximately from cycle 0 to cycle 200 in the three executions. This corresponds to a period within which the agent was able to recover the lesser number of lost objects.
2. *Phase 2* includes approximately from cycle 200 to cycle 700 or 900, depending on the execution. This corresponds to a period within which the agent began to recover nearly all the objects that it lost and which were susceptible of being recovered.
3. *Phase 3* includes approximately from cycle 700 or 900 to cycle 1500. This third and last phase corresponds to a period within which a considerable decrease in the total number of objects lost by the agent was observed, falling to almost zero near the end of the runs.

Each stage is further discussed below.

Phase 1.

During phase 1, the agent began interacting with its world by using only its three basic schemas (shown in Figure 7). From there, it started creating its first developed schemas by generalization, differentiation, and deletion of those, where the associated expectations

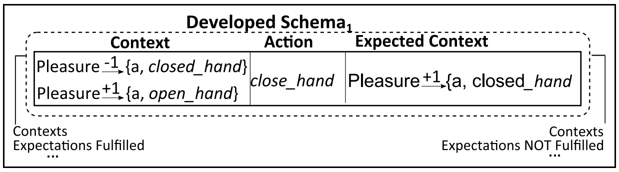

Figure 9. Schema created during phase 1.

were not fulfilled most of the times. Accordingly, by the end of this first phase, the agent had built one single developed schema (the same happened throughout the three executions), which is shown in Figure 9. This first schema associates the situation of having opposed affective responses caused by the same object (unpleasantness due to the loss of an element that had been grasped, and pleasure for detecting the same object on an ongoing basis, but now with the hand open), with the action of closing the hand and the expectation of recovering the affective response of pleasure resulting from grasping again the object of interest. In other words, this schema contains in itself the knowledge that (1) the agent is able to recover the pleasant objects that were lost but which are still sensed with the open hand, and (2) it may recover said objects by closing its hand. With the creation of this new schema, the agent has learned to recover tangible objects which it is interested in. This situation leads it to a second phase.

Phase 2.

The creation of the schema constructed in the previous phase resulted in, on one hand, the agent to enter a period within which it began to recover nearly all the objects lost and which were susceptible of being recovered (see Figure 8). On the other hand, it also caused a change in the behavior of the agent's expectations, which, as shown in Figure 10 (wherein the number of expectations is contrasted to the number of expectations fulfilled), began to be fulfilled 100% of the times from the creation of said schema. These two situations (learning how to successfully recover the objects of interest and having the expectations 100% of the times on an ongoing basis) led the agent to become able to interact with its environment during N_C cycles (for these experiments, $N_C = 250$), without the need to modify its knowledge, resulting in the achievement of a status of cognitive equilibrium for the first time (indicated in the bottom portion of the graphs shown in Figure 10). As a result of having reached said state, the agent gradually became able to find partial matches among the current contexts and its developed schema (shown in Figure 9). One of said partial matches (when the agent sensed an object with its hand opened and it used the schema of Figure 9 to deal with this situation) resulted in the creation of a second schema, shown in Figure 11. This associates the situation of having an affective response of pleasure triggered by touching any object with the open hand, with the action of closing the hand, and with the expectation of having again an affective response of pleasure caused by touching the same object, but now with the closed hand. The construction of this second schema caused the agent to begin closing its hand when it came into contact with any of the objects of interest, but not as a result of a reflex behavior (through the use of a basic schema) but rather because of a developed behavior having an expectation associated therewith.

Again, with the creation of this second schema, the agent managed to interact with its environment for N_C additional cycles without having the need to modify its knowledge, leading, for a second time, to a cognitive equilibrium state, near the end of phase 2 (see Figure 10). As a result of entering such state, the agent became able to identify partial matches between the current contexts and the two recently created developed schemas. One of such partial matches (when the agent sensed an object with its hand closed and it used the schema of Figure 11 to deal with this situation) resulted in the creation of a third schema, shown in Figure 12. The new schema associates the situation of having an affective response of pleasure triggered by touching any object with the closed hand, with the action of closing the hand, and with the expectation of maintaining the affective response of pleasure caused by holding the same object.

The construction of this third schema resulted in that, from that point onward, the agent began to maintain its hand closed when it was holding an object of its interest, which was then released when an emotional reaction of boredom was triggered (please note that this emotional reaction is triggered when the agent maintains a hold on a same object over several cycles, 10 cycles for these experiments). In other words, the agent learned to hold on to the objects of its interest, which led to the third and final stage.

Phase 3.

This is characterized in that it was a period within which a considerable decrease in the total number of objects lost by the agent was observed and resulted from the creation of a third schema through which it was able to keep a hold of the objects that were interesting for it. To show the rising of this new behavior, we have created the graphs shown in Figure 13, wherein the average number of cycles over which the agent kept a hold of an interesting object along the execution is shown.

In said graphs, we can see that, from the creation of a third schema, near the start of phase 3, the average number of cycles over which the agent kept a hold of the interesting objects was increased.

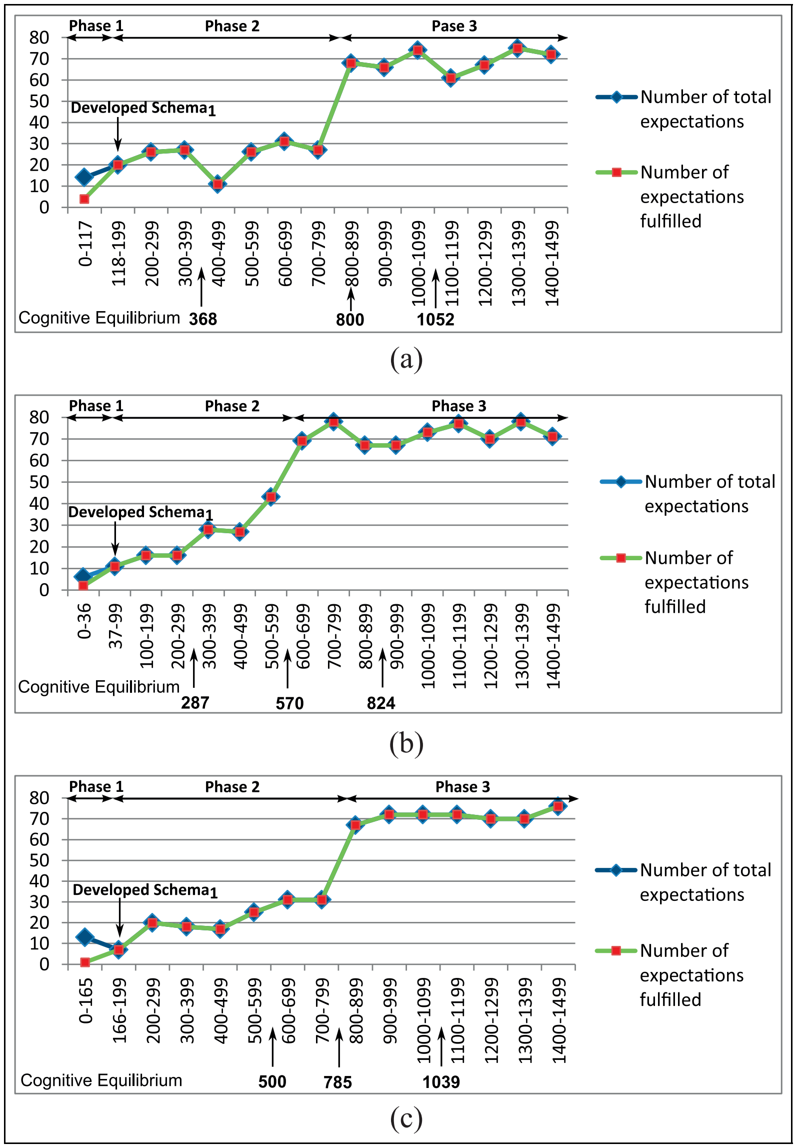

Figure 10. These graphs show the number of total expectations created by the agent in contrast to the number of expectations fulfilled in each of the three executions: (a) execution 1, (b) execution 2, and (c) execution 3.

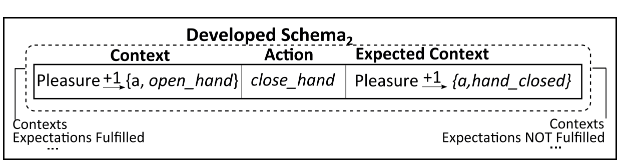

Figure 11. Schema created during phase 2.

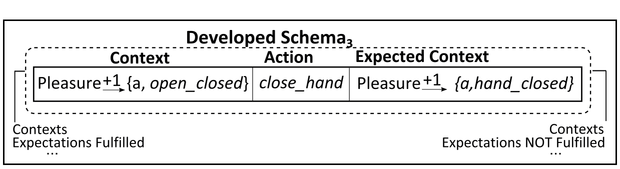

Figure 12. Schema created by the end of phase 2.

After interacting with its environment over 250 additional cycles, the agent once again entered a state of cognitive equilibrium, remaining in said state during 500 cycles more, thus concluding its execution.

5.2.4. Summary. In this second set of experiments in which the agent could only touch but not see its world, it learned how to

- Recover the pleasant objects that it was holding (it learned that this can only be done with the objects that are let go but which it continues to sense with the open hand),
- Hold the objects of its interest which are in contact with the palm of its hand, and

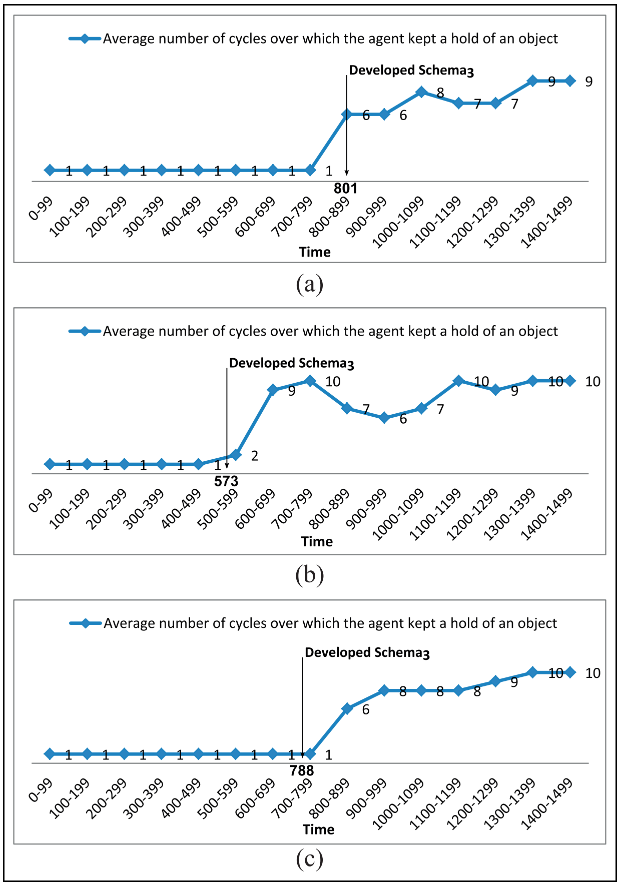

Figure 13. These graphs show the evolution in the average number of cycles over which the agent kept a hold of the interesting object along the three executions: (a) execution 1, (b) execution 2, and (c) execution 3.

- To hold on to the objects of its interest.

5.3. *Third set of experiments: the agent can see and touch its world*

The third set of experiments consisted in configuring the agent so that it could both see and touch its world. Development was considered completed when it remained in a state of cognitive equilibrium during the last 2000 cycles. In order to carry out the experiments, the agent was configured with the parameters of Dev E-R shown in Table 2 (except for parameter N_C, which was given the value of 2000), as well as the following initial knowledge.

5.3.1. Initial knowledge. The agent was initialized with the three basic schemas shown in Figure 7, wherein in this case, variable A represents any visual element defined as $A = \{\text{color, size, movement, position}\}$, or any tangible element defined as $A = \{\text{texture}, \textit{hand\_status}\}$. Additionally, its knowledge base was initialized with the schemas developed when it could only see and when it could only touch the world around it (generated in the first and second set of experiments). In other words, initialization was started with the knowledge of how to recover and maintain the visual and tangible objects of agent's interest (including the skills of visually following the objects of interest, centering them in the visual field, as well as to hold on to the objects that come in contact with the hand and keeping them held until another object attracted its attention or until it became bored). The reason for the above was that, in this experiment, we were interested in observing the set of behaviors that arise when the agent has constructed and stabilized both its visual and tactile schemas.

Finally, physical or external actions that could be performed by the agent included all the possible head and hand movements.

5.3.2. Virtual world setup. This time, the agent was allowed to interact again in three separate executions within the living room of the house shown in Figure 6. The agent was in a sitting position in the middle of the environment, with the head looking to the front and with its hand outside the visual field. All the objects were static, except for agent's hand, which was moving in random directions at some points in time. Later in this run, the balls began to move in the same way they behaved during the second set of experiments (refer to section 5.2.2).

5.3.3. Results. Upon starting, the first observation we found was that when agent's hand came into the visual field, that part of its body caught its attention and it began to follow that luminous element with head movements (using the developed schemas that were available at initialization). This behavior is exemplified in Figure 14. It is important to note that, up to this moment, the agent sees its hand moving, not exactly because it is a part of itself (as it has not developed any knowledge structure which allows it to distinguish its own body from the rest of the objects in the environment) but because the hand catches its attention due to the color, size, and movement of the hand itself, as if it were any other element present in the virtual world.

After 500 cycles, the balls began to move to enter into contact with the agent's hand. From that moment, the behavior of the agent consisted in holding the objects that were in contact with its sensor and then releasing the items when it lost interest in them, and in following the visual elements that caught its attention. In other words, the agent continued to interact with the environment by using all the knowledge it was initialized with. After 1500 additional cycles, the agent reached a state of cognitive equilibrium, causing the schemas stored in memory to be considered stable, thus being the agent capable of (1) representing in the same

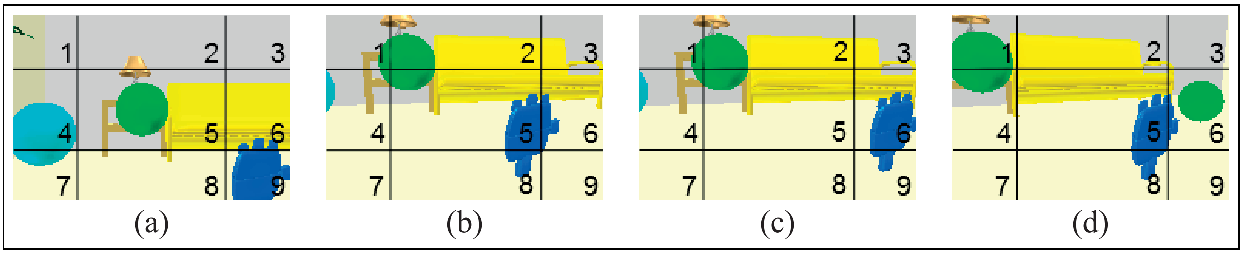

Figure 14. This image shows how the agent sees its hand moving: (a) The agent sees its hand at position 9 of its visual field. Then use one of its developed schemas to keep it. (b) The action taken, a movement of its head to the right and down, makes the hand to be placed in the center of its visual field. (c) The agent moves its hand to the right, now placing it in position 6 of his visual field. Then use one of their developed schemas to preserve it. (d) The executed action, a movement of its head to the right, causes the hand to be placed back into the center of its visual field, where it pays attention to it again.

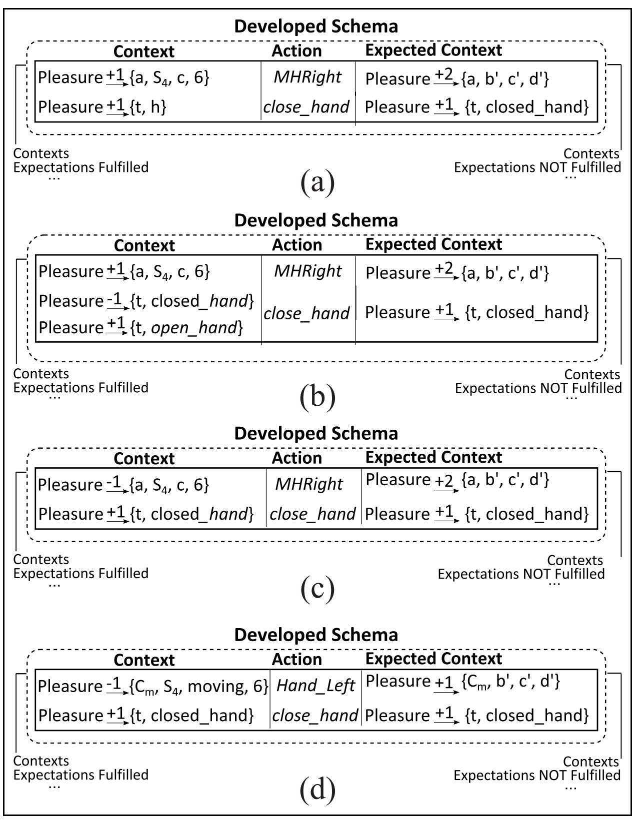

Figure 15. Schemas created when the agent was able to both see and touch its world, which helped it maintain and recover objects seen and probably touched in position 6 of its visual field: (a) preserve the visual object and the tactile object, (b) preserving the visual object while recovering the tactile object, (c) recovering the visual object (with a movement of the head) while maintaining the tactile object, and (d) recovering the visual object (with a movement of the hand) while maintaining the tactile object.

Current-Context both visual and tactile data, and (2) finding partial matches with the stabilized structures. These new capacities opened room for the creation of 32 new schemas, 4 per each position of the peripheral areas within the visual field. Figure 15 shows the four schemas developed corresponding to position 6. The remaining schemas (the other 28) only differ in terms of position and associated actions needed to maintain and/or recover the object(s) that triggered interest (as the actions to be performed depend on the position of the visual field in which the object is seen, as illustrated in Figure 16).

The first set of schemas, shown in Figure 16(a), were created as follows. The moment when the agent saw an object that caught its attention while sensing that it was touching something with its hand (whether open or closed), a *Current-Context* was created, which included two affective responses of pleasure: one triggered by the visual element and the other triggered by the tactile object (e.g. as exemplified in Figure 17). This context represented a new situation that the agent had never faced, for which it had no schema to determine how to act. This led the agent to try to adapt its current knowledge and perception of the world to face with this new situation by finding a partial match with two schemas: one to preserve the visual object and another to preserve the tactile item (as exemplified in Figure 17). In Piaget's terminology, this means that the agent felt inclined to simultaneously maintain what it was seeing and what it was touching. When the expectations associated with both schemas were fulfilled, an emotional reaction of surprise was generated, resulting in a new structure (see Figure 17), which represents the knowledge about how to maintain simultaneously the pleasant objects that the agent is seeing and touching. For instance, when the agent saw an object in position 6 within its visual field while touching something in the palm of its hand, the schema shown in Figure 15(a) would indicate that the agent could maintain both objects by simultaneously moving the head to the right while closing its hand. In the event that the element being touched was the same as the object being seen, then the use of these schemas led to have the agent holding the object in its hand while centering it within the agent's visual field (by moving the head).

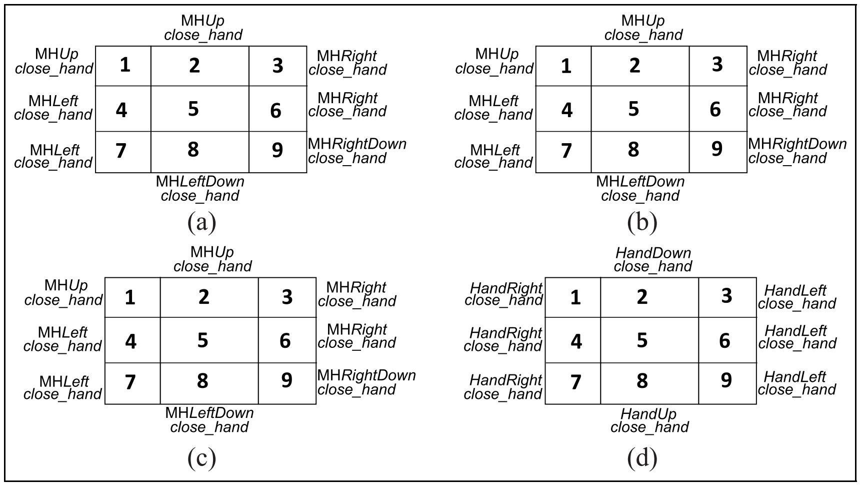

Figure 16. Set of schemas created when the agent was able to both see and touch its world, for all the positions within the visual field: (a) preserving both the visual and the tactile object, (b) preserving the visual object while recovering the tactile object, (c) recovering the visual object (with a movement of the head) while preserving the tactile object, and (d) recovering the tactile object (with a movement of the hand) while preserving the visual object.

The second and third set of schemas shown in Figures 15(b), 15(c), 16(b), and 16(c) were created similarly to the case described above. That is to say, they were constructed as a result of the agent facing an unknown situation, thus responding by making a partial match with two of its structures available in memory, as illustrated in Figures 18 and 19. However, each of them represented different behaviors. On one hand, the second set of schemas contains the knowledge about how to maintain the visual object liked while recovering the tactile object. For example, if the agent saw an object in position 6 within its visual field while letting go the object in the palm of its hand, the schema shown in Figure 15(b) indicated that the agent could again feel pleasure with both objects by simultaneously moving the head to the right while closing its hand (provided that the agent could continue to sense the desired element with the hand open). In the event, the object that was being touched by the agent was the same that was being seen by it, and then the use of these schemas caused the agent to be seen as if it was releasing and taking again the object of its interest. On the other hand, the third set of schemas represents the knowledge about how to recover the pleasant visual object while maintaining the tactile object. For example, if the agent saw its hand grabbing an object in position 6 and during that cycle, the agent chose to randomly move the hand out of its visual field unwantedly, then the use of these schemas made us see the agent pulling its hand out of and then back to the its visual field (by moving its head) while holding an object.

The creation of the fourth set of schemas is a very interesting case, since, unlike the other ones, these were constructed as a result of a partial match between only one schema in memory, allowing the agent to find an alternative way to recover visual objects having a feature in particular: They were of a shade of blue called C_m. The way in which these arouse is illustrated in Figure 20, where we can see the moment when the agent lost a pleasant object of C_m color in position 6 while feeling pleasure for an object held in its hand, and the agent chose to use only one of the schemas whose expectation was maintaining the tactile element. During that same cycle, the agent randomly moved the hand (to the left) in such a manner that it "accidentally" caused the C_m color to come back into the agent's visual field. At that moment, a new general schema was created, indicating the agent that any object lost from position 6 could be recovered, while maintaining the object held in hand, if the agent moved its hand to the left and closed it. In time, this schema was differentiated into one indicating that this was only possible when the object lost was of C_m color, the same color of agent's hand. Similarly, the agent learned that there was a blur in particular (of C_m color) which could be controlled (recovered and preserved) by moving its hand. This resulted in a functional differentiation between the spot representing the hand and any other visual element.

5.3.4. Summary. Briefly, the behaviors learned when the agent was able to both see and touch its world were as follows:

- Visually following its hand by moving its head.
- Centering within its visual field (by moving its head), the object being held.
- Seeing within its visual field how its hand grabs and releases the object of interest.

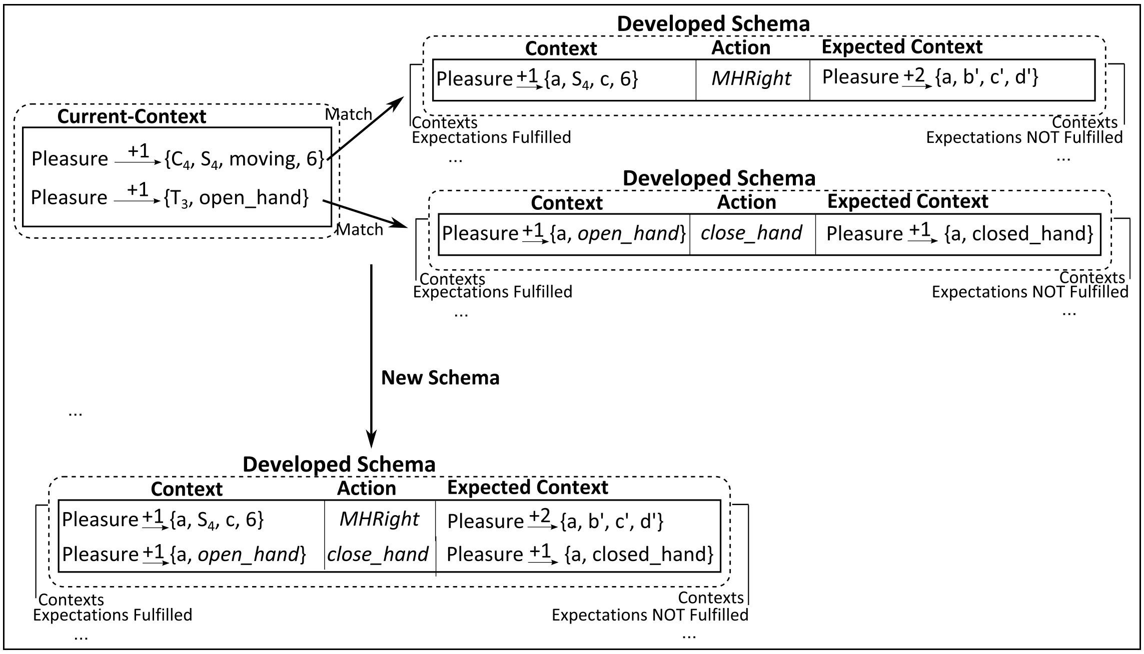

Figure 17. Exemplifies the creation of the first set of schemas developed involving both pleasure for what it sees as for what it touches.

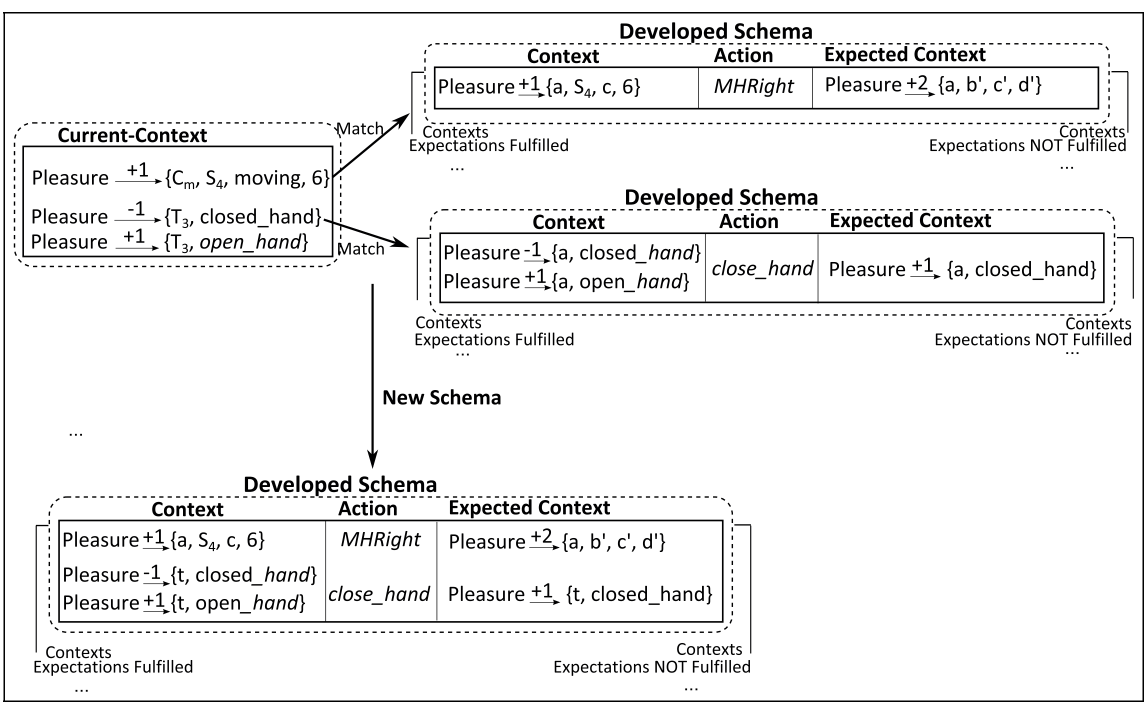

Figure 18. Exemplifies the creation of the second set of schemas developed involving both pleasure for what it sees as for what it touches.

- Seeing how its hand grabbing an object goes out of its visual field, and then recovering that image by moving its head.
- Seeing how its hand grabbing an object goes out its visual field, and then recovering that image by moving its hand.

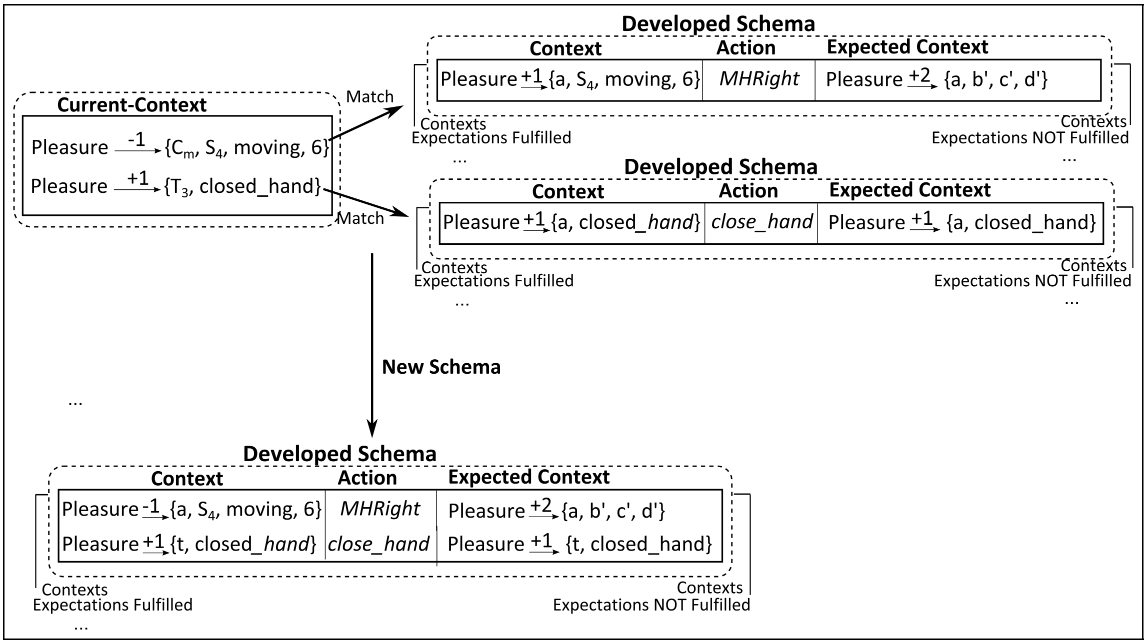

Figure 19. Exemplifies the creation of the third set of schemas developed involving both pleasure for what it sees as for what it touches.

5.3.5. Development from basic schemas. In this section, we present some preliminary, but interesting, results about how visual and tactile processes affect each other when the agent (1) can see and touch the world, (2) is initialized only with the three basic schemas of Figure 7, and (3) can attend one visual object and one tactile object at the same time, since the beginning of the execution.

In this experiment, visual and tactile schemas developed independently and in parallel, until the agent entered a state of cognitive equilibrium for the first time. As a result, the agent developed the following new behaviors:

- Recovering pleasant objects that went out by any area of the periphery of its visual field, by moving the head toward the right direction.
- Recovering the visual image of its hand, by moving the hand itself toward the correct direction according to the position where it was last seen.
- Closing the hand when it was touching an object, while it was seeing something (not necessarily the same object) in any area of its field of vision.

After the first stabilization, visual and tactile processes continue to develop independently to acquire skills about how to preserve pleasant visual and tactile stimuli (through partial matches performed with the previously stabilized schemas), but also they started to cooperate with each other.

Skills acquired independently of each modality are as follows:

- Visually following and centering in the visual field the objects of interest.
- Centering its hand in its visual field by moving the hand.

Once previous schemas were created, the agent started to use them in a cooperative way, in sequence one after the other, showing the following behavior:

1. Centering an object of interest in the visual field by moving the head.
2. Centering also its hand by moving the hand. This resulted in a situation where both objects were in the center of the visual field (sometimes the hand occluded the ball), and most of the times these were in contact with each other.
3. Closing the hand to hold on the object that it was seeing and touching in the center of its visual field.
4. This line of development took the agent approximately twice as long as in the previous experiments. We are working in creating strategies to reduce the time.

6. Discussion

According to Piaget, the hand (together with the mouth, the eye, and the ear) is one of the most crucial instruments used by intelligence. Its core task is grasping, which is developed following five stages—which do not correspond to defined ages, but whose sequence is fundamental, except for stage number 3 (Piaget, 1936/

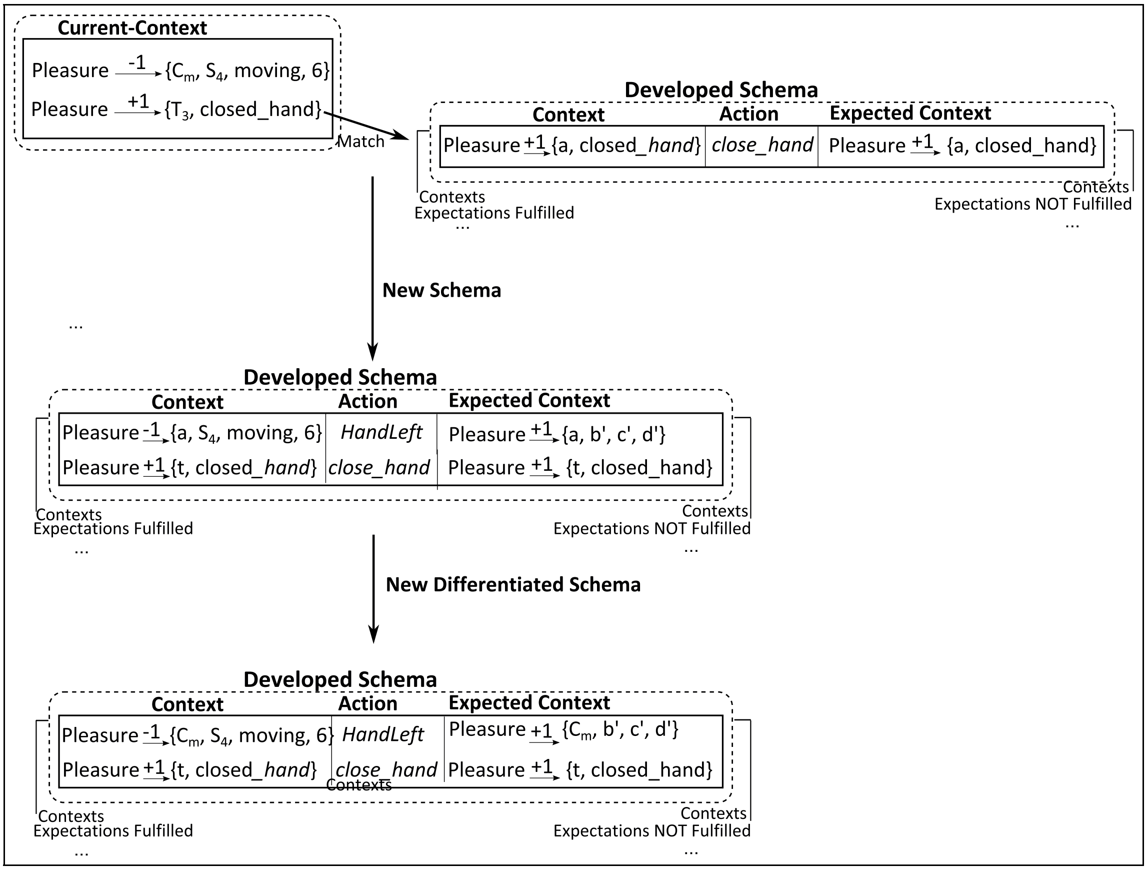

Figure 20. Exemplifies the creation of the fourth set of schemas developed involving both pleasure for what it sees as for what it touches.

1952). In this section, we shall discuss the results obtained within the context of said theory.

6.1. Emergence of the first eye–hand coordination

6.1.1. Stage 1: impulsive movements and pure reflex. During this first stage, the newborn closes the hand upon feeling pressure on the palm, as a result of the grasping reflex that we are all born with. The newborn also moves by impulse both arms, hands, and fingers. In our agent, we observed that, at the beginning of the executions, it kept on randomly moving its hand and closing it whenever its tactile sensor detected the presence of an object. The action of closing its hand was caused by the use of the basic schema representing the grasping reflex. This behavior was noticed for a short time (between 36 and 165 cycles) until the agent faced for the first time a situation wherein, while holding an object, opened the hand automatically and the object, now released, remained in contact with the hand. At that moment, a *Current-Context* was created, describing a new situation: displeasure due to having lost the object that was being held but also pleasure as the open hand was still in contact with said item. That is, the agent was facing opposing emotions (see Figure 9). In this situation, during *Engagement*, the agent had the option to form a partial match between the *Current-Context* with any of the three basic schemas available in its memory, as shown in Figure 21. The result of (1) selecting the second basic schema and (2) choosing the random action of closing the hand is the formation of the new schema illustrated in Figure 9. The same occurs when it is selected the third basic schema. With the creation of this new structure, the agent has learned to recover tangible objects which it is interested in. This situation leads the agent to move on to the second stage of grasp development.

6.1.2. Stage 2: grasping just for grasping and vision is adapted to hand movements. In this second stage, the baby manages to grasp and maintain the objects in its hand without seeing them and without attempting to take them to its mouth. During this period, coordination between vision and general hand movements starts to appear. That is, baby manages to visually follow their own hands, but can only keep them within the visual field by moving the eyes around, not the hands. In other words, vision adapts to hand movements, but a reciprocal action by the hands is not yet certain.

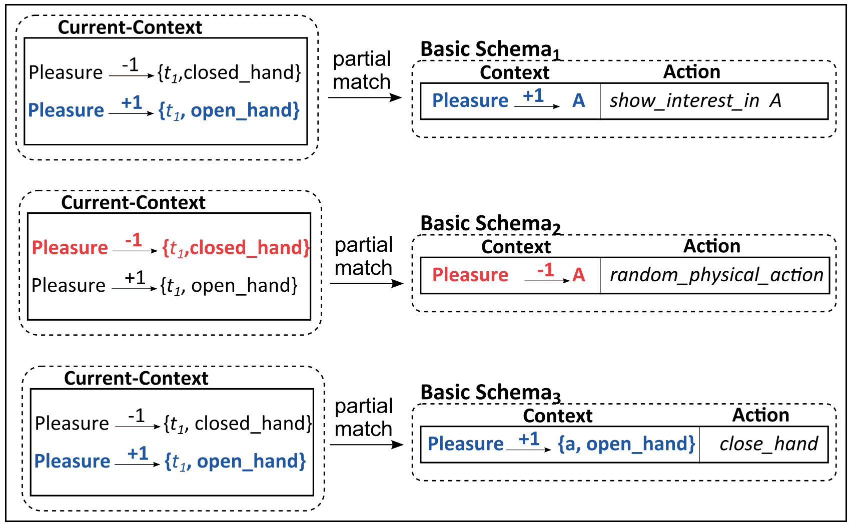

Figure 21. Illustration of the potential partial matches between a *Current-Context* representing opposing emotions and basic schemas. The partial matches are considered so because only one of the two affective responses in the *Current-Context* corresponds to the single affective response available in *Basic Schema*$_1$, *Basic Schema*$_2$, and *Basic Schema*$_3$. Matches are shown in red and blue.

In our agent, we observed that, once it learned how to recover the interesting objects that it released, and once this knowledge became stabilized after repeatedly releasing and recovering different elements, it learned how to keep a hold on them. Additionally, in the third set of experiments, as soon as we activated agent's capacity of sight and touch, it applied all the knowledge acquired from the previous experiments and began to visually follow its hand by moving the head. However, at that point, the hand represented to the agent just a spot, as the rest of the objects in its surroundings.

6.1.3. Stage 3: coordination between pressure and suction, and limitation of hand movements into the visual field. During this third stage, the baby manages to grasp objects and take them to the mouth, as well as taking the elements that its mouth is sucking. Regarding vision, during this stage, babies already exert influence on hand movements. For example, looking at the hand seems to increase its activity, or, on the contrary, it may limit its movements within the visual field. With this step forward in baby's development, it can be noticed that, when infant's hand randomly appears within its visual field, the hand tends to remain on sight. This is the first sign of a reciprocal adaptation, with the hand tending to preserve and repeat movements seen by the eye, while the eye tends to look at everything the hand does. In other words, hand tends to assimilate into its own schemas the visual domain, just as the eye assimilates into its own schemas the hand domain.

To this regard, it is quite interesting to notice how our agent assimilated visual data into its tactile schemas, and vice versa. We can see this in the structures shown in Figure 15, where we notice that the contexts are now formed by emotional reactions of pleasure and disliking, both toward visual and tactile elements, with the associated actions including head and hand movements, and the same occurs with the expected context. The formation of these new structures led the agent to learn how to center within its visual field (by moving its head), the object being held; watch, in the center of the visual field, how its own hand releases and then recovers the object of its interest; watch how its own hand goes out of the visual field grasping an object and then coming back into the visual field by moving the head; and watch how this last behavior can be performed by moving the hand instead of the head. The use of this set of new behaviors by our agent allowed us to watch it interact with the objects grasped, most of the times within the center of the visual field. Moreover, by creating the last schema, a functional differentiation between the spot represented by the hand and any other one began to manifest. This means that the agent learned that there was a blur, having very particular visual characteristics, which could be controlled by moving its hand.

Agent's development came that far. During the fourth stage, babies get the ability to take an object when they simultaneously see their hands and the desired object; while during the fifth and last stage, they acquire the ability to take any seen object without limitations related to the position of the hand (it can even be outside of their visual field). We believe that our agent may achieve the last two stages of the development of eye–hand coordination, if we grant it capacities of differentiation between means and ends and goal-oriented behaviors. This shall constitute part of our subsequent efforts.

6.2. Developmental path

The developmental path of new behaviors is essential in Piaget's theory. For this reason, in this section, we shall discuss the path followed by all the behaviors learned by the agent.

In the first and second set of experiments, wherein the agent could only see or touch the world around it, we could see that the earliest skills it acquired were the result (1) of having lost the objects of interest, (2) of their "accidental" recovery (by using one of the basic knowledge structures available to the agent), and (3) of the generalization/differentiation of such experiences. Accordingly, the agent first learned how to recover into its visual field the items that had gone out thereof, and to recover the elements that were held and then released. The developmental path of these two new behaviors is illustrated in the top portion of Figure 22.

Later, our agent entered for the first time into a state of cognitive equilibrium, thus triggering its capacity of finding partial matches with the stabilized schemas. In other words, the agent became capable of using its built knowledge about how to recover interesting objects to face unknown situations. The foregoing resulted in the acquisition of two new behaviors: (1) visually following the interesting objects and (2) holding an object that was touched by the palm of the hand (see the middle portion of Figure 22).

Thereafter, the agent entered for the second time into a state of cognitive equilibrium, during which it learned two new abilities (as a result of making partial matches between its current situation and past experiences): (1) centering into the visual field static objects of its interest and (2) maintaining a hold on an object (see the bottom portion of Figure 22).

Finally, during the third set of experiments, the agent entered once more into a state of equilibrium and remained in that state for several cycles. As a result, its visual and tactile schemas were considered as stable, thus becoming capable of representing, in its *Current-Context*, objects that caught its attention, both visual and tactile. This led the agent to learn four new behaviors (which appeared again as a result of partial matches): (1) centering within its visual field (by moving its head), the object being held; (2) watching, in the center of the visual field, how its own hand releases and then recovers the object of its interest; (3) watching its own hand grasping an object going out of the visual field and then coming back by moving the head; and (4) watching its own hand grasping an object going out of its visual field and then coming back in sight by

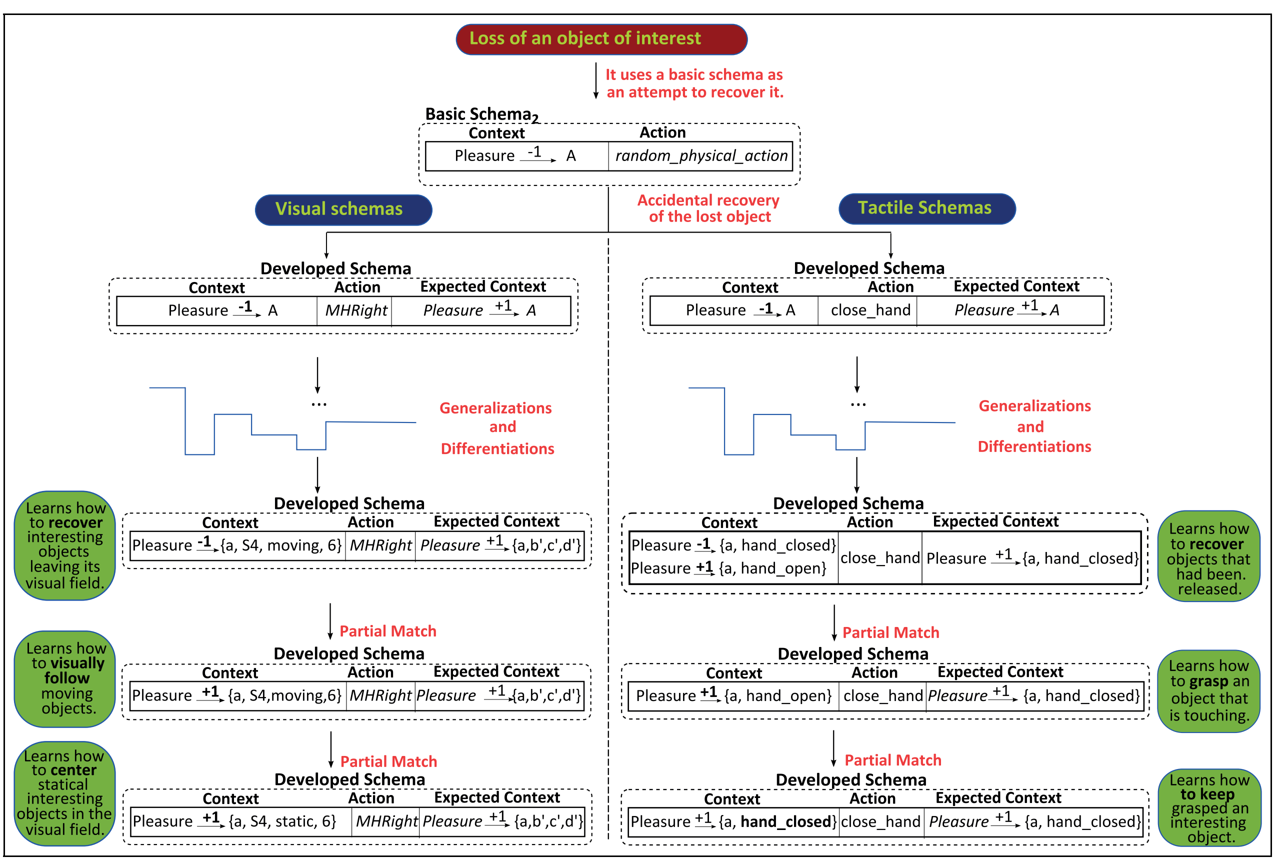

Figure 22. Exemplifies the developmental path of the abilities acquired by the agent.

moving the hand (Figures 17–20 show the origin of these skills).

Thus, it was then possible to trace a developmental path, which allows us to observe how the construction of new behaviors depend on and derive from known experiences.

6.3. Development as a creative process

We are interested in the study of the creative process employing computers. Surprisingly, it is hard to find computational research projects that focus on studying the genesis of the creative process. As far as we know, this is the first computational model that attempts to contribute in that area that we refer to as early-creative behavior. As an interesting characteristic, the ER-Model model that we employ in this work has been originally used to develop an automatic storyteller. So, one can picture a continuous that represents computer models of creativity at different states during the development of skills, where Dev E-R is located in one extreme while our storyteller is located in the opposite extreme. In this way, we can compare both systems. The main purpose of our storyteller is to develop a coherent narrative where conflicts start to rise, until they reach a climax, and then they are sorted out; so, conflicts are essential to progress a plot. It is interesting to notice that in Dev E-R, conflicts are the force that pushes the agent to produce new schemas. Thus, in a sense, in ER-Model, conflicts also arise, reach a climax, and then they decay. In our storyteller, knowledge structures are represented in terms of emotional links and tensions between characters, while in Dev E-R such structures are represented as emotional links between the agent and its environment. This seems to suggest that emotions and conflicts might play an important role in the representation of the agents' world. The capacity of matching partial knowledge structures in memory provides to both, Dev E-R and our storyteller, the opportunity to deal with novel situations. In the same way, there are important differences between both systems: Our storyteller has a sophisticated process of reflection, while in Dev E-R the advancement of reflection is part of the agent's development, and the storyteller represents much more abstract information than Dev E-R (e.g. the general structure of the story).

In Aguilar and Pérez y Pérez (2014) it is presented a set of useful criteria to assess whether the behaviors generated by an agent may be considered as creative. We will discuss each of them to evaluate the results obtained in this article.

6.3.1. Novelty. A behavior is considered novel if it did not exist explicitly in the initial database of knowledge of the agent (Pérez y Pérez, 2014). In the experiments, the agent was initialized with three basic schemas. By the end of the executions, it had constructed at least 58 new structures that did not exist in the initial database of knowledge of the agent. Hence, under this criterion, all behaviors the agent learned are considered novel.

6.3.2. Utility. A behavior is considered useful if it serves as basis for the construction of new knowledge that gradually leads the agent to acquire new skills that are typical of the following stage of development (cf. Pérez y Pérez, 2014). Thus, the knowledge structures developed by the agent are considered useful, as they allowed it to go from predefined or innate behaviors (typical of the first substage of the sensory-motor period) to body-based behaviors (typical of the second substage of the sensory-motor period) and to behaviors involving external objects (typical of the third substage of the sensory-motor period).

6.3.3. Emergence. Following Steels (1990), a behavior emerges when its origin may not be traced back directly to the components of the system, but rather, it is the result of the way in which such components interact with each other. In the Dev E-R model, the learning of different behaviors depends on a number of factors, notably, (1) environmental properties, (2) physical characteristics of the agent, and (3) current knowledge. In this way, because the new behaviors are not preprogrammed and they are all context-dependent, we may conclude that the behaviors learned by the agent emerged as a result of the way in which the different system components interacted with each other.

6.3.4. Motivations. Amabile and Collins (1999) distinguished two types of creativity: (1) intrinsically motivated and (2) extrinsically motivated. Following them, in this work a behavior developed by an agent is considered creative if it appears as a result of an intrinsic or extrinsic motivation. Our model represents this feature because the emotional reaction of surprise and the intrinsic motivation of cognitive curiosity trigger in the agent the need to modify or construct new schemas.

6.3.5. Adaptation to a new environment. The ability to adapt ourselves to our environment has been traditionally deemed as a condition needed for truly creative behavior (Runco, 2007); similarly, Leonora Cohen describes adaptation as the closest synonym of creativity (Runco, 2007). In Piaget's theory, adaptation is defined in terms of the processes of assimilation and accommodation. We suggest that, in order to consider a behavior developed by an agent as creative, it must acquire such behavior as a result of a process of adaptation to the environment.

The schemas developed by the agent were created as a consequence of it facing unknown situations and reacting to them: (1) by assimilating the new circumstance to the previously acquired knowledge (through a process of searching the memory for a schema, which represents a situation similar to the one being faced in the *Current-Context*) or (2) by accommodating the knowledge in such a way that it may adjust to the new experience (thus creating a new schema, or differentiating, generalizing, or deleting an existing one). Therefore, we suggest that they are originated as a result of the agent's adaptation to its world.

6.4. Comparison with other methods

In this section, we compare four characteristics of developmental agents: (1) initial state and knowledge representation, (2) motivational components, (3) learning processes, and (4) stage transition mechanisms.

6.4.1. Initial state and knowledge representation. Developmental agents can be classified into two groups: those that start interacting with the environment from *tabula rasa* (i.e. they are initialized with an empty "mind," and therefore all its knowledge is the result of learning through their experiences and sensorial perceptions) and those that start with "innate" knowledge. Examples of the first group include Perotto and Alvares (2006), Modayil and Kuipers (2007), and Mugan and Kuipers (2008). Typically, these agents work with raw data, in contrast to the ones of the second group which usually abstract the world into discrete states and actions (Guerin & McKenzie, 2008). Our agent belongs to the latter.

Among the most representative works that belong to the second category is Drescher's (1991) work and some subsequent systems based on it such as Holmes and Isbell (2005), Guerin and McKenzie (2008), and Lee et al. (2012), which although they report that their system does not start with any explicit innate knowledge, it has the pre-programmed behaviors of palmar reflex and holding the objects until someone removes them or they are dropped by accident. Commonly, these agents define their knowledge structures as schemas that are comprised by three main parts: pre-conditions (named by some authors as context), an action, and post-conditions (named by some authors as result). Contexts and results represent some condition of the world (e.g. visual, tactile, and proprioceptive information). In this way, the schema represents that, when the pre-conditions are satisfied, the agent might perform the action; as a result, the world is modified according to the post-conditions. A typical example of these kinds of structures is shown in Figure 23. Drescher's (1991) schema mechanism and Holmes and Isbell's (2005) improvement of it are initialized with one schema for each action the agent can perform, and with empty contexts and results. This initial "empty" knowledge structures are points of departure for building contentful schemas. The same holds for Guerin and McKenzie's (2008) agent, which is initialized in a similar way, although four extra schemas that model reflexes (e.g. sucking, grabbing, gazing) are also included. Our agent represents its knowledge as a context, an action, and a result, and it is initialized with one schema that represents the palmar reflex, but, unlike the others, it (1) defines the contexts in terms of more general attributes such as affective responses, emotional reactions, and current motivations, and (2) includes two schemas to model the tendency to preserve and to recover pleasant stimulus. That is, our agent perceives its world in terms of representations of emotions and motivations triggered by the stimuli present in the environment, and not in terms of the particular features of the objects it sees and touches. We believe that these characteristics make our model more flexible. The following lines elaborate this idea. Figure 23 illustrates a schema that shows that when a green object is located in a given position (x, y), then the agent can perform the action "reach"; the features describing the context are very specific. We wonder why does a green object located on (x, y) trigger such an action? We claim that the decision of what to do depends on more elaborated circumstances that can be (at least partially) represented in terms of affective reactions. If a green (or blue or white, or big or small) object produces curiosity, attraction, need, and so on, then the agent probably attempts to reach it. However, the same object, under different circumstances, might generate fear, anxiety, nervousness, and so on; in such cases, the agent might try to avoid it. Schemas with very specific information, like the one presented in Figure 23, can hardly represent the complexity of the circumstances surrounding an object; more abstract structures, like the ones used by Dev E-R, show more flexibility and adaptability to diverse situations. For instance, our agent can generalize that any item, not just those in green, can be reached by the same action (c.f. Figure 23); in the same way, the capacity of performing partial matches allows dealing with new situations. Some models attempt to sort out this problem by employing a predefined affective reaction. For instance, in the work of Law, Shaw, Earland, Sheldon, and Lee (2014), each time the agent sees a new object, the system triggers novelty. However, this generalization hardly reflects what one observes in the world. Following Pérez y Pérez and Sharples (2001) and Küger et al. (2011), we suggest that models of developmental agents should represent the same context at different levels of abstraction. Specific contexts allow registering the type of information necessary for implementing, for example, a robot's arm, while abstract representations characterize more elaborated contexts. In this way, if we are able to link them, we can exploit the best of both approaches.

6.4.2. Motivational components. Since one of the main characteristics of developmental agents is that they are

Pre-conditions	Action	Post-conditions
Green object at (17.5, 72.4)	Reach to (17.5, 72.4)	Hand at (17.5, 72.4) Green object at (17.5, 72.4) Touch sensation

Figure 23. The typical structure of the schemas defined in Drescher's work and all subsequent models based on it.
Source: Law et al. (2014).

not given any explicit goal or task, then how and why should they perform any action and learn new skills? This is where intrinsic motivations play an important role in these kinds of systems. Some researchers have explored the idea of using novelty as a driver (see, for example, Law et al., 2014), others have used curiosity (see, for example, Oudeyer, Kaplan, & Hatner, 2007), others have explored the idea of having an intrinsic motivator that rewards the discovery of environment affordances (see, for example, Hart & Grupen, 2011), and some others have proposed to use emotions such as happiness, fear, and sadness to shape behavior (see, for example, Ahn & Picard, 2006; Gao & Edelman, 2016). In the case of our agent, conflict is what moves it to act. In particular, this happens (1) when Jacques is in a state of pleasure and then something happens that prevents it to continue in that satisfactory situation, and (2) when its expectations differ from "reality." So, a very important characteristic of our model is that if there is no conflict, there is no learning. As a consequence of this, our agent only builds new schemas when it faces these kinds of situations while interacting with the environment, in contrast to other agents which work, finding all possible contexts and results caused by the execution of all actions (see, for example, Drescher, 1991) or by maximizing a reward such as novelty. Currently, Dev E-R works in a constrained environment where search heuristics and optimization procedures might get some similar results; however, in a more open environment, where an agent can find countless different situations, we believe that our approach will be more effective because of the use of the contextual information to generate and differentiate schemas. In future works, we will run some experiments to test our assumption.

6.4.3. Learning processes. Early sensorimotor learning can be considered as a process that discovers the consequences of actions, as well as the conditions that these consequences depend on. Several learning methods have been proposed to solve this problem. For instance, Drescher (1991) uses marginal attribution; McClelland (1995), Shultz et al. (1995), Parisi and Schlesinger (2002), and Chaput (2004), among others, use neural networks, and some others like Guerin and McKenzie (2008) and Hart and Grupen (2011) use reinforcement learning. In this research, we propose a different approach which consists in implementing learning (an essential mechanism for adaptation and cognitive development) as a creative process. Using this new approach, our agent learns new skills by (1) using a process of generalization and differentiation of schemas, and (2) using its knowledge of past experiences to deal with new similar, but not identical, situations (i.e. using its knowledge of past experiences to deal with new similar, but not identical, situations).

The first one differs from other approaches in that in our model, new schemas start as a generalization of a sole experience, which then may split into particular schemas, and then they may continue in this process of generalization and differentiation until they stabilize (as summarized in Figure 4). In contrast, works such as Sheldon and Lee (2011) and Guerin and McKenzie (2008) can only modify schemas in one direction, from particular to general. An exception is the Constructivist Anticipatory Learning Mechanism (CALM) system (Perotto et al., 2007), which implements three methods for learning: differentiation, adjustment, and integration. The main differences are that (1) in the CALM system, the processes of differentiation and generalization occur every time an expectation is not met, while in Dev E-R they only occur when the used schema exceeds a certain percentage of failure, giving the agent more flexibility to respond to indeterminacies in the environment; (2) generalization (called adjustment in CALM) replaces, by the undefined symbol #, those properties in the expectation that are different from the perceived ones, while in Dev E-R the replacement is performed based on the properties registered in the two extra structures of successful and failure contexts attached to the schemas, which the CALM system does not have; (3) the generalization process only occurs when a differentiation cannot be performed because all the elements in the context are specified, while in Dev E-R it can happen at any time of the execution; and (4) when a differentiation is performed, the more general schema is always preserved, causing the CALM system to require more memory than Dev E-R. Furthermore, since the CALM system has not been tested in environments and with agents which develop the very first abilities related with vision and touch, it is difficult to make a direct comparison with Dev E-R.

The second learning strategy differs from other works in that most of them only perform a total match between the current situation and the schema's context; and from the ones that do partial matches, due to its very specific knowledge representation, as previously discussed, are limited to discover irrelevant sensor values (e.g. Guerin & McKenzie, 2008). On the contrary, our agent benefits from its more general knowledge representation making it possible, for example, to learn to preserve pleasant objects by using its experience to recover them.

6.4.4. Stage transition mechanisms. Most computational works that try to mimic children development are focused on learning mechanisms within a single developmental stage. Among the most recent and complete projects is that of Law et al. (2014). In their model, they use physical constraints to deal with the complexity of identifying which motor movements cause which effects. These prevent the agent to learn everything at the same time and also help it to bootstrap between stages. For instance, at the start of the experiment, their robot can only move its eyes. Once it achieves control over such a skill, a new competence is activated: first, its capacity to move its head; then, its ability to move its neck; then the shoulder, torso, and so on.

The Dev E-R model uses constraints to let the agent learn new skills of increasing complexity but, unlike the previous example, restrictions are applied to cognitive capacities rather than physical ones. Jacques does this by detecting when it has reached into a state of cognitive equilibrium, which activates the possibility of performing partial matches with its new stabilized schemas. That is, its cognitive capability of using its stable previous experience with similar, not identical, situations is released. So, in Dev E-R, cognitive development emerges as a consequence of the agent going from a state of equilibrium to disequilibrium and back to equilibrium, as Piaget suggests.

We believe that both kinds of constraints, physical and cognitive, can complement each other in such a way that a more complete agent can be created. This is a strategy we think may help to scale our model when more senses are included or when the number of actions increases.

7. Conclusion

Dev E-R is a computational model of early cognitive development, implemented as a creative process. It was inspired by the theories of Jean Piaget (1936/1952) and Leonora Cohen (1989). In a prior paper (Aguilar & Pérez y Pérez, 2015), it was explored its functionality in an artificial agent which could only see (but not touch) the world around it. In this article, our main interest was to study its potential by using it in an agent which could only touch (but not see) the world around it, and in a separate agent which could do both, seeing and touching. The results from the experiments described herein have allowed us to observe the generality of said model, in the sense that it, based on the sensorial capabilities of the agent, was able to learn, on one hand, new behaviors associated with vision and, on the other hand, new behaviors associated with the sense of touch, and finally, the agents showed new behaviors based on both touching and seeing. These latter behaviors represent the first eye–hand coordination skills identified by Piaget. Moreover, the developmental path followed by the agent matches the one described by the renowned researcher. Hence, Dev E-R is a model which allows us to study relevant aspects of the development of an agent from a novel perspective. This model includes the possibility of observing how the environment and the sensorial capabilities of the agents affect its development, while enabling us to follow, on a step-by-step basis, the construction of its knowledge. The results obtained in this article are quite exciting, although there is still much work to be done.

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