DER ZUSAMMENHANG ZWISCHEN VISUELL-RÄUMLICHER OBJEKTWAHRNEHMUNG UND MOTORIK IM SÄUGLINGSALTER

Theresa Marie Gerhard

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Erstgutachterin: Frau Prof. Dr. Gudrun Schwarzer

Zweitgutachterin: Frau Prof. Dr. Katja Fiehler

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Gießen, den 24. September 2018

Theresa Marie Gerhard

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Inhaltsverzeichnis

I. Synopse

1. Einleitung

Von Geburt an finden wir uns in einer Welt wieder, in der erfolgreiches Handeln die Entdeckung, Verarbeitung und Nutzung visuell-räumlicher Informationen unabdingbar macht. Wir sind stets mit der Aufgabe konfrontiert uns in unserer Umwelt zurechtzufinden, müssen durch sie hindurch navigieren, die Position der uns umgebenden Objekte bestimmen, sie ergreifen und zielgerichtet manipulieren können. Schon früh ist es daher notwendig adäquate räumliche Fähigkeiten auszubilden, damit wir in der Lage sind diese alltäglichen Anforderungen zu bewältigen. Räumliche Fähigkeiten und ihre Entwicklung spielen jedoch nicht nur im Rahmen einer fortlaufenden Anpassung des Individuums an seine Umgebung eine wichtige Rolle, sie sind gleichsam evolutionär von Bedeutung, bilden eine zentrale Komponente in Modellen zur menschlichen Intelligenz und erhalten aufgrund ihres prädiktiven Werts erhöhte Aufmerksamkeit in akademischen Leistungsfeldern, wie der Mathematik und den Naturwissenschaften (z.B. Newcombe, Uttal & Sauter, 2013; Wai, Lubinski & Benbow, 2009). Die Untersuchung der Entwicklung räumlicher Fähigkeiten im Säuglingsalter sowie die Bestimmung relevanter Entwicklungsfaktoren ist vor diesem Hintergrund ein zentrales Anliegen entwicklungspsychologischer Forschung.

Die Sichtweise, dass sich Entwicklungsveränderungen in verschiedensten Fähigkeitsbereichen aus einer Interaktion des Individuums mit seiner Umwelt und damit einhergehenden Umwelterfahrungen ergeben, ist heute unter Entwicklungsforschern weit verbreitet. Entsprechende Interaktionen beruhen dabei originär auf der Ausführung motorischen Verhaltens, das heißt auf der Basis von Handlungen mit der Umwelt (Adolph & Franchak, 2017). Dieser grundlegenden Auffassung war schon Piaget (1952), bei dem die Ursprünge der entwicklungspsychologischen Erforschung räumlicher Fähigkeiten anzusiedeln sind. Nach seiner Theorie erfolgen Prozesse der Wissensausbildung über die räumliche Beschaffenheit von Objekten durch die Internalisierung der sensomotorischen beziehungsweise Handlungserfahrungen des Säuglings mit jenen Umweltobjekten. Ausgehend von Piagets Erkenntnissen, lassen sich heute eine Vielzahl an Forschungsbemühungen zum Zusammenhang von motorischen Prozessen mit Fähigkeiten aus dem Bereich der visuell-räumlichen Objektwahrnehmung finden (s. Campos et al., 2000; Kubicek & Schwarzer, 2018).

Die Studien der vorliegenden Arbeit reihen sich in diese Forschungstradition ein und erweitern, unter Berücksichtigung fein- und grobmotorischer Entwicklungsprozesse, das Wissen hinsichtlich zweier Bereiche der visuell-räumlichen Objektwahrnehmung im Säuglingsalter: Der Wahrnehmung von dreidimensionalen, realen Objekten und ihren zweidimensionalen Abbildungen (Studie 1a und Studie 1b) und der kognitiven Fähigkeit zur geistigen Transformation der räumlichen Orientierung von Objekten, der mentalen Rotation (Studie 2).

1.1 Entwicklungsaspekte visuell-räumlicher Objektwahrnehmung

Mit der Geburt betreten wir eine komplexe, dreidimensionale Umgebung voll mit Objekten. Eine zentrale Aufgabe des visuellen Systems ist es, seine Wahrnehmungsfähigkeiten schnell an diese neue Umgebung und die in ihr befindlichen Objekte anzupassen. Da das Sehen in seiner Natur dreidimensional ist, kann auch die Objektwahrnehmung nicht außerhalb des Kontexts räumlicher Wahrnehmung verstanden werden. Die Verarbeitung und Nutzung räumlicher Objektinformationen wie Tiefe, Distanz zum Beobachter oder Orientierung im Raum, müssen von Säuglingen zunehmend erlernt werden, um sie zwecks Navigation und der Auswahl zielorientierter Handlungen einsetzen zu können (Frick, Möhring & Newcombe, 2014; Schwarzer, 2014).

Damit Objekte räumlich wahrgenommen werden können, obwohl optische Eindrücke auf der Retina nur zweidimensional abgebildet werden, extrahiert das visuelle System verschiedene Tiefenhinweise. Aufgrund ihres adaptiven Werts scheint sich die Entwicklung dieser Mechanismen zum Großteil innerhalb der ersten 6 Lebensmonate zu vollziehen (Norcia & Gerhard, 2015). Bereits früh nutzen Säuglinge die durch eigene Bewegung (Bewegungs-parallaxe) und die Bewegung von Objekten (radiale Bewegung) erzeugten kinetischen Tiefenhinweise. Die Sensitivität gegenüber diesen bewegungsinduzierten Tiefeninformationen wird ab ungefähr 2 bis 3,5 Monaten angenommen (Brosseau-Lachaine, Casanova & Faubert, 2008; von Hofsten, Kellman & Putaansuu, 1992; Shirai, Kanazawa & Yamaguchi, 2008). Ein zudem zentraler Mechanismus zur Wahrnehmung von räumlicher Tiefe ist die durch das beidäugige Sehen entstehende binokulare Disparität (Stereopsis). Ihr liegt eine Verrechnung der beiden leicht voneinander abweichenden Netzhautbilder aufgrund der lateral zueinander verschobenen Augen zugrunde (Goldstein, 2008a). Säuglinge nutzen sie für das Ablesen der dreidimensionalen Form von Objekten mit ungefähr 4 Monaten (Kavšek, 2011; Yonas, Arterberry & Granrud, 1987). Am Längsten bedarf es jedoch der Wahrnehmungsentwicklung komplexer monokular-statischer beziehungsweise bildhafter Tiefenhinweise wie Verdeckung, linearer Perspektive, oder gewohnter Größe. Zwischen 5-7 Monaten haben Säuglinge die visuellen Mechanismen ausgebildet, um auch auf Basis dieser Tiefeninformationen räumlich wahrzunehmen (Kavšek, Yonas & Granrud, 2012).

Die bewusste Wahrnehmung visuell-räumlicher Objektinformationen erfordert neuronale Verarbeitungsprozesse, die entlang eines dual angelegten ventralen und dorsalen

Pfades stattfinden. Während der ventrale Pfad den primären visuellen Kortex (V1) mit temporalen und präfrontalen Arealen verbindet, verläuft der dorsale Pfad ebenfalls von V1 ausgehend in Bereiche des Parietalkortex (Goldstein, 2008b). Typischerweise werden entlang des ventralen Pfads Informationen hinsichtlich objektidentifizierender Merkmale wie Farbe, Größe, Textur, Form oder Tiefe verarbeitet. Er wird daher als *Was-Strom* bezeichnet. Entlang des dorsalen Pfads, auch als *Wie/Wo-Strom* bekannt, werden hingegen raumzeitliche Informationen der Bewegung und Lokalisation von Objekten verarbeitet (Wilcox & Biondi, 2015a; Xu, 1999). Dabei ist wichtig, dass zwischen beiden Verarbeitungspfaden Informationen ausgetauscht werden (Cloutman, 2013). Für eine erfolgreiche Interaktion mit Objekten im Alltag ist es notwendig diese nicht nur zu identifizieren, sondern auch zu lokalisieren. Die Differenzierung in einen ventralen und dorsalen Verarbeitungspfad und die Annahme ihrer Interaktion ist jedoch nicht nur für das Gehirn von Erwachsenen annehmbar. Neuronale Bildgebungstechniken verweisen auf ähnliche Muster im Säuglingsgehirn, die allerdings noch gewissen Entwicklungsprozessen unterliegen (Wilcox & Biondi, 2015a).

Aus einer evolutionären Perspektive können nach Newcombe und Kollegen räumliche Fähigkeiten in zwei funktional distinkte Bereiche eingeteilt werden, die sich auch innerhalb der Individualentwicklung abbilden lassen (s. Newcombe et al., 2013). Dazu gehört zum einen die Repräsentation und Transformation von *Zwischen-Objekt Beziehungen*. Sie betreffen extrinsische Informationen bezüglich der Position von Objekten, aber auch des eigenen Selbst zum umgebenden Raum. Den zweiten Bereich bilden Fähigkeiten zur Repräsentation und Transformation von *Inner-Objekt Beziehungen*. Hierbei geht es um intrinsische Informationen hinsichtlich der Form und internen Objektstruktur, die unabhängig vom Umgebungsraum verarbeitet werden und deren meist beforschte Fähigkeit diejenige zur mentalen Rotation darstellt (Frick et al., 2014). Die Entwicklung beider Bereiche ist für die alltägliche Funktionsfähigkeit des Menschen von großer Bedeutung. Während die Verarbeitung von Zwischen-Objekt Beziehungen für das Erinnern von Objektorten und eine erfolgreiche Navigation durch die Umwelt relevant ist, steht bei den Inner-Objekt Beziehungen die Manipulation von Objekten im Kontext des Werkzeuggebrauchs im Fokus (Newcombe et al., 2013).

1.2 Visuell-räumliche Objektwahrnehmung und Motorik

Der Zusammenhang zwischen motorischer und psychologischer Entwicklung ist von Beginn des Lebens an fundamental und vielfältig. Fein- und grobmotorische Fertigkeiten, als immanente Bestandteile unseres Handlungssystems, stehen in reziproker Verbindung mit perzeptuellen, kognitiven und sozialen Fähigkeiten. Sie sind daher für das sich ausbildende

Verständnis des Säuglings seiner physikalischen und sozialen Umwelt zentral (Adolph & Franchak, 2017; Libertus & Hauf, 2017). Experimentelle Befunde mit gesunden Säuglingen belegen unter anderem positive Beziehungen zwischen grobmotorischen Fertigkeiten und Spracherwerb (z.B. He, Walle & Campos, 2015; Libertus & Violi, 2016) sowie sozialer und emotionaler Entwicklung (Campos, Bertenthal & Kermoian, 1992; Karasik, Tamis-LeMonda & Adolph, 2016; Walle, 2016). Motorisches Verhalten zeigt zudem spezifische Zusammenhänge zur Entwicklung visuell-räumlicher Fähigkeiten aus den Bereichen der Inner- und Zwischen-Objekt Beziehungen. Objekte zielgerichtet ergreifen und sich selbstinduziert fortbewegen zu können, ermöglicht Säuglingen zunehmend ihre Umwelt und die in ihr befindlichen Objekte zu explorieren und so spezifische Lernerfahrungen zu sammeln (Bushnell & Boudreau, 1993; Gibson, 1988). Die Fähigkeit zwei unmittelbar benachbarte Objekte als räumlich distinkt wahrzunehmen ist bereits bei 3-4 Monate alten Säuglinge mit ihrer visuellen und oralen Exploration während des eigenständigen Haltens von Objekten assoziiert (Needham, 2000). Mehr noch fördern feinmotorische Fertigkeiten und Möglichkeiten zur manuellen Objektexploration die Wahrnehmung der dreidimensionalen Struktur von Objekten bei 4,5-7,5 Monate alten Säuglingen (Soska, Adolph & Johnson, 2010), die Fähigkeit zur mentalen Rotation bei 6-9 Monate alten Säuglingen (Möhring & Frick, 2013; Schwarzer, Freitag & Schum, 2013), aber auch die visuelle Vorhersage von Objektpositionen im Alter von 7-8 Monaten (Kubicek, Jovanovic & Schwarzer, 2017a). Positive Assoziationen bestehen darüber hinaus zur grobmotorischen Entwicklung, insbesondere zur selbstinduzierten Fortbewegung. Die aktive Suche und Positionsbestimmung von Objekten im Raum ist bei Säuglingen im Alter von 8-9 Monaten mit Erfahrungen in den Fortbewegungsformen des Krabbelns auf Händen und Knien und des Gehens verbunden (Bai & Bertenthal, 1992; Kermoian & Campos, 1988). Gestützt und erweitert werden diese Befunde durch Evidenz, dass auch bei rein passiver, visueller Vorhersage von Objektpositionen, Zusammenhänge zum selbstinduzierten Krabbeln bei 9-monatigen Säuglingen bestehen (Kubicek, Jovanovic & Schwarzer, 2017b). Die selbstinduzierte Fortbewegung, in Form von Krabbeln und des Gehens mit Hilfestellung, scheint sich zudem förderlich auf die kognitive Fähigkeit der mentalen Rotation bei Säuglingen im Alter von 8-10 Monaten auszuwirken (Frick & Möhring, 2013; Schwarzer, Freitag, Buckel & Lofruthe, 2013; Schwarzer, Freitag & Schum, 2013).

Das Zusammenspiel von motorischen Fertigkeiten und visuell-räumlicher Objektwahrnehmung lässt sich jedoch nicht nur anhand gesunder Personen abbilden. Es wird ebenso bei Betrachtung von Personengruppen mit motorischen und visuellen Einschränkungen deutlich. Bei Säuglingen mit Spina bifida, einer angeborenen Verschlussstörung des

Neuralrohrs, kommt es durch eine Paralyse der unteren Extremitäten zu bedeutsamen Verzögerungen in der Entwicklung grobmotorischer Fertigkeiten, unter anderem des Krabbelns (Campos, Anderson & Telzrow, 2009; Wiedenbauer & Jansen-Osmann, 2007). Befunde zeigen, dass bei einem entsprechend verspätetem Einsetzen des Krabbelns Schwierigkeiten in der räumlichen Repräsentation von Objekten, der Objektpermanenz, auftreten können (Campos et al., 2009). Bestimmte objektbezogene, räumliche Verarbeitungsdefizite persistieren dabei möglicherweise bis ins fortgeschrittene Kindesalter. So fanden sich geringere Leistungen in einer Aufgabe zur mentalen Rotation bei 8-14 Jahre alten Kindern mit Spina bifida im Vergleich zu gesunden Kontrollkindern, die sich durch ein manuelles Rotationstraining jedoch angleichen ließen (Wiedenbauer & Jansen-Osmann, 2007). Auch Verzögerungen in der grobmotorischen Entwicklung durch eine angeborene Fußfehlstellung scheinen mit 12 Monaten zu spezifischen Problemen in der räumlichen Objektsuche zu führen (Dillmann, Peterlein & Schwarzer, 2018). Nicht zuletzt bedingt fehlendes binokulares Tiefensehen und damit eine Beeinträchtigung in der visuell-räumlichen Wahrnehmung per se, motorische Defizite bei 3-7 Jahre alten Kindern mit frühkindlichem Innenschielen (Dillmann et al., 2017) sowie bei älteren Kindern und Erwachsenen (O'Connor, Birch, Anderson & Draper, 2010).

Neuronale Bildgebungsstudien untermauern entsprechende Verhaltensbefunde zum Zusammenhang von visuell-räumlicher Objektwahrnehmung und Motorik, in dem sie darauf verweisen, dass für beide Prozesse ähnliche Bereiche des menschlichen Gehirns rekrutiert werden. Es konnte beispielsweise demonstriert werden, dass die mentale Rotation von Objekten bei Erwachsenen Aktivität in neokortikalen motorischen Arealen hervorruft, die auf die Durchführung motorischer Simulationsvorgänge während der Aufgabenbearbeitung schließen lässt (Richter et al., 2000; Zacks, 2008).

1.3 Erklärungsansätze für einen Zusammenhang von visuell-räumlicher Objektwahrnehmung und Motorik

Die Annahme eines bedeutsamen Zusammenspiels von motorischen Prozessen und perzeptuellen sowie kognitiven Fähigkeiten ist zentraler Bestandteil wichtiger theoretischer Ansätze über die kindliche Entwicklung. Piaget (1952) betonte in besonderer Weise die Rolle von Handlungen für die Wissensgenese im Kind. Er stellte erstmals zentrale Fragen, etwa wie Säuglinge zu Beginn des Lebens Objektpermanenz erlangen, das heißt die Fähigkeit zur mentalen Repräsentation der überdauernde Existenz eines Objekts und seiner Eigenschaften, wie seiner Position und Ausdehnung im Raum. Nach Piaget sind hierfür die ersten beiden Lebensjahre essenziell, die er als sensumotorische Phase bezeichnet. Ganz in der Auslegung seiner konstruktivistischen Theorie nahm Piaget an, dass Säuglinge und junge Kinder in dieser Phase sensomotorische Lernerfahrungen über die raumzeitliche Assoziation von Handlungen mit hierdurch ausgelösten Sinnesempfindungen generieren. Die Internalisierung dieser Erfahrungen bildet dann die Grundlage der kindlichen Wahrnehmung sowohl von sich selbst, als auch von der Umwelt und den in ihr befindlichen Objekten (Schwarzer & Degé, 2014). In der Tradition Piagets kann der Ansatz *Travel broadens the mind* von Campos und Kollegen (2000) verstanden werden. Dieser betont die Rolle selbstinduzierter Fortbewegung (z.B. des Krabbelns) für die kindliche Wahrnehmungs- und Denkentwicklung. Das Einsetzen der selbstinduzierten Fortbewegung, die als wichtige Handlung begriffen wird, ermöglicht eine Reihe an neuen Wahrnehmungserfahrungen. Gleichzeitig ist für eine optimale Anpassung an die neue Bewegungsform eine Reorganisation psychologischer Prozesse notwendig, wie dem Arbeitsgedächtnis, der Aufmerksamkeit und räumlicher Kodierungsstrategien. Auf diese Weise entwickeln sich anfangs noch rudimentärere Wahrnehmungs- und Denkfähigkeiten immer weiter aus (vgl. Schwarzer & Degé, 2014) und werden aufrechterhalten (Anderson et al., 2013). Betont wird allerdings, dass das Auftreten der selbstinduzierten Fortbewegung für die Entwicklung kindlicher Fähigkeiten keineswegs eine notwendige, wohl aber eine hinreichende Bedingung darstellt (Adolph & Hoch, im Druck; Campos et al., 2000), die in gesunden Kindern den üblichen Entwicklungsweg kennzeichnet.

Schließlich findet sich auch in der Sichtweise der *Embodied cognition* die Annahme wieder, dass es für das Voranschreiten von kognitiven Entwicklungsprozessen einer Interaktion der Person mit ihrer Umwelt bedarf (Smith & Gasser, 2005; Thelen, 2000). Entwicklungsfortschritte im Säugling werden auch nach dieser Auffassung als Ergebnis sensomotorischer Aktivität verstanden, die der Säugling auf seine Umgebung ausrichtet und die ihm bereits vorgeburtlich erste Lernerfahrungen hinsichtlich der intrauterinen Umwelt und seines eigenen Körpers ermöglicht (Needham & Libertus, 2011; Smith & Gasser, 2005).

Eine weitere wichtige Perspektive, die einen Bezugsrahmen für die positiven Effekte von Motorik auf räumliche Objektwahrnehmungsfähigkeiten bietet, ist die ökologische Theorie der Wahrnehmungsentwicklung von Eleanor Gibson (s. Adolph & Kretch, 2015; Gibson, 1988). Nach Gibson besteht die Funktionalität der Wahrnehmung darin, Informationen über Objekte, Ereignisse und Orte in unserer Umwelt zu sammeln und zu erkennen, wie wir sie handlungsorientiert einsetzen können (Gibson & Rader, 1979). Daher spezifiziert sie in ihrem Ansatz, was genau von einem Stimulus im Laufe der Entwicklung wahrgenommen wird und verwendet hierfür den Begriff der *Affordanz*. Die Affordanz eines Stimulus bezeichnet sein Handlungsangebot an den Wahrnehmenden. Die Wahrnehmung von Affordanzen schafft somit eine direkte Verbindung zwischen Wahrnehmungs- und motorisch vermittelten Handlungsprozessen (Gibson, 1988). Gibson bezeichnet daher den *Perceiver as performer* (Gibson & Rader, 1979) und charakterisiert die Wahrnehmung von Affordanzen als aktiven Prozess. Während bestimmte und für das Überleben zentrale Affordanzen angeborenermaßen vom Säugling erkannt werden (z.B. das menschliche Gesicht), generiert sich der Großteil ihrer Wahrnehmung über aktive Umweltexploration. Folgerichtig besteht nach Gibsons Theorie ein stetiger, wechselseitiger Austausch zwischen der Wahrnehmung von Affordanzen und den motorischen Explorations- und Interaktionsmöglichkeiten des Säuglings (Schwarzer & Degé, 2014). Als eine interessante Weiterentwicklung des Gibson'schen Ansatzes gilt die *Theorie der dynamischen Systeme*. Sie begreift den Menschen als Gesamtsystem, das sich durch die Interaktion mit seiner Umwelt sowie interner Reorganisation in ständiger Anpassung befindet (De Bot, Lowie & Verspoor, 2007). Für die Herausbildung neuer Wahrnehmungsfähigkeiten betont sie ebenfalls die Kopplung von Wahrnehmung und Handlung (s. Schwarzer & Degé, 2014), die über Explorationsverhalten erfolgt (Adolph, Eppler, Marin, Weise & Wechsler Clearfield, 2000) und daher eng mit der Entwicklung des motorischen Systems verknüpft ist.

1.4 Zielsetzung der Studien

Eingebettet in empirische und theoretische Evidenz einer positiven Beziehung von motorischer Entwicklung und Fähigkeiten der visuell-räumlichen Objektwahrnehmung, ermöglichen die vorliegenden Studien einen vertiefenden Einblick in zwei visuell-räumliche Objektwahrnehmungsprozesse aus dem Bereich der Inner-Objekt Beziehungen im Säuglingsalter. Die Studien 1a und 1b befassten sich mit der Wahrnehmung von sich in ihrer Tiefenstruktur unterscheidenden realen, dreidimensionalen Objekten und deren zweidimensionalen Abbildungen (im Weiteren oft Darstellungsformat oder Objektformat). Auf diese Weise sollten neue Erkenntnisse über die ökologische Validität von Objektbildern als Repräsentationen für reale Objekte im Säuglingsalter gewonnen werden. Studie 1a betrachtete erstmals die grundlegende visuelle Verarbeitung von realen Objekten und ihren fotorealistischen Abbildungen in einer Stichprobe von 7 und 9 Monate alten Säuglingen. Studie 1b fokussierte anschließend auf die Frage, ob das Darstellungsformat Einfluss auf die spontane, visuelle Aufmerksamkeitszuwendung bei 7-monatigen Säuglingen nimmt und inwiefern die Zuteilung von Aufmerksamkeit mit den feinmotorischen Erfahrungen der Säuglinge korrespondiert, die sie während der visuell-manuellen Exploration von Objekten im Alltag generieren. Studie 2 widmete sich der kognitiven Fähigkeit zur geistigen Transformation der räumlichen Orientierung von Objekten, der mentalen Rotation. Es wurde erstmals systematisch untersucht, ob der Prozess der mentalen Rotation bei 9-monatigen Säuglingen vergleichbar zu dem in Erwachsenen abläuft und, ob die Erfahrungen der Säuglinge in der selbstinduzierten Fortbewegungsform des Krabbelns auf Händen und Knien mit diesem Prozess interagieren.

2. Studien 1a und 1b – Die visuelle Wahrnehmung von realen Objekten und ihren Abbildungen im Säuglingsalter

Der Einsatz zweidimensionaler, bildhafter Objektrepräsentationen als Äquivalent für dreidimensionale, reale Objekte hat in der Erforschung von Aufmerksamkeit, Gedächtnis und visueller Wahrnehmung lange Tradition. Reale Objekte unterscheiden sich jedoch in einigen Merkmalen von ihren Abbildungen. Dazu zählen, dass reale Objekte reichhaltiger an visuellen Tiefeninformationen durch binokulare Disparität und Bewegungsparallaxe sind, dass sie im Vergleich zu Objektbildern einen konsistenten Tiefeneindruck über binokulare und monokulare Tiefenhinweise vermitteln und dass sie, gemäß Gibson, ein größeres Handlungsangebot an den Wahrnehmenden stellen (vgl. Snow et al., 2011). Verhaltens- sowie neurophysiologische Untersuchungen haben auf der Basis experimenteller Befunde die ökologische Validität von Abbildungen als gleichwertige Entsprechung für reale Objekte in der Tat zunehmend in Frage gestellt. Vielfach zeigte sich bei Patienten mit visueller Objektagnosie ein *Real-object advantage*, also bessere Erkennungsleistungen für reale Objekte gegenüber Bildern (Chainay & Humphreys, 2001; Humphrey, Goodale, Jakobson & Servos, 1994; Riddoch & Humphreys, 1987; Servos, Goodale & Humphrey, 1993). In gleicher Weise ist die Präsentation realer Objekte positiv assoziiert mit episodischer Gedächtnisperformanz (Snow, Skiba, Coleman & Berryhill, 2014), mit Einschätzungen der Objektvalenz (Bushong, King, Camerer & Rangel, 2010) und der kortikalen Verarbeitungsgeschwindigkeit während der visuellen Objekterkennung bei Kleinkindern (Carver, Meltzoff & Dawson, 2006). Diese Studien lassen zurecht vermuten, dass reale Objekte und ihre Abbildungen vom Menschen nicht gleichwertig visuell wahrgenommen werden. Inwiefern Säuglinge im ersten Lebensjahr Hinweise auf eine distinkte Wahrnehmung von realen Objekten und Bildern dieser Objekte zeigen, ist bisher jedoch nicht explizit untersucht worden. Diesem Ziel widmeten sich Studie 1a und Studie 1b.

2.1 Studie 1a – Distinct visual processing of real objects and pictures of those objects in 7- to 9-month-old infants (Gerhard, Culham & Schwarzer, 2016)

Das Darstellungsformat eines Objekts hat womöglich Einfluss auf seine Verarbeitung. Einen ersten Beleg für eine distinkte neuronale Verarbeitung von visuell präsentierten realen Objekten und Bildern der Objekte lieferten Snow und Kollegen (2011). Sie untersuchten mittels funktioneller Magnetresonanztomografie die charakteristische Reduktion der hämodynamische Aktivierung (BOLD-Signal) während wiederholter, visueller Präsentation realer und bildhafter Objektstimuli im Erwachsenengehirn. Dieser wiederholungsabhängige Effekt, auch bezeichnet als Wiederholungsunterdrückung, erlaubt je nach Auftreten Aussagen über die Sensitivität relevanter Hirnstrukturen für bestimmte Stimulusmerkmale (z.B. Nordt, Hoehl & Weigelt, 2016). Eine solche Wiederholungsunterdrückung gilt jedoch auch als Indikator für schwächere, schnellere, oder auch präzisere Verarbeitungsvorgänge (Grill-Spector, Henson & Martin, 2006). Die Ergebnisse der Studie lieferten in der Tat differentielle Effekte hinsichtlich der neuronalen Verarbeitung realer Objekte und ihrer Abbildungen im objektspezifischen lateralen okzipitalen Komplex (LOC). Während die in vorherigen Studien bereits beobachtete Wiederholungsunterdrückung für bildhafte Objekte auch hier nachgewiesen wurde, zeigte sie sich für reale Objekte deutlich reduziert bis gar nicht (Snow et al., 2011). Unklar war bisher allerdings, inwiefern solch distinkte Verarbeitungsmuster möglichweise schon im Säuglingsalter auftreten. Auf Grundlage der Befunde von Snow und Kollegen (2011) und theoretischen Überlegungen, die im Rahmen der Erforschung von Objektrepräsentationen bedeutsame Parallelen zwischen wiederholungsabhängigen Effekten in funktioneller Bildgebung und Säuglingshabituation annehmen (Nordt et al., 2016; Turk-Browne, Scholl & Chun, 2008), widmete sich Studie 1a erstmals der visuellen Habituation und damit der visuellen Verarbeitung von realen Objekten und deren Abbildungen bei Säuglingen im ersten Lebensjahr.

Unter Verwendung eines visuellen Habituationsparadigmas mit anschließendem Paarvergleich, wurden 7- und 9-monatige Säuglinge zunächst an ein reales Spielzeugobjekt oder dessen fotorealistische Abbildung habituiert. In der sich anschließenden Testphase sahen sie das Habituationsobjekt gepaart mit demselben Objekt im anderen Format (real oder bildhaft). In beiden Phasen wurden die Blickzeiten der Säuglinge auf die jeweils präsentierten Objekte erfasst, die für die Analyse des Blickverhaltens im Test in prozentuale Blickpräferenzwerte überführt wurden. Für die Habituationsphase lieferten die Daten Hinweise auf eine distinkte Verarbeitung visuell präsentierter Objekte unterschiedlichen Formats für beide Altersgruppen (Abbildung 1). Zu Beginn der Habituation fixierten Säuglinge, die an ein reales Objekt habituiert wurden, dieses bedeutsam länger als Säuglinge, die ein Objektbild präsentiert bekamen. Am Ende der Habituation zeigten sich hingegen keine Blickzeitunterschiede zwischen den beiden Habituationsgruppen mehr. Beide Gruppen wiesen somit einen signifikanten Abfall der Blickzeiten vom Anfang zum Ende der Habituationsphase auf. Dieser war bei Säuglingen, die an ein reales Objekt habituiert wurden jedoch stärker ausgeprägt (Interaktion: $p < .05$). Die Ergebnisse des visuellen Paarvergleichs im Test zeigten eine allgemeine Präferenz für reale Objekte gegenüber Bildern, erneut in beiden Altersgruppen. Unabhängig davon, ob die Säuglinge zuvor bereits an das reale Objekt oder dessen Bild habituiert worden waren, schauten sie in dieser Phase länger auf den realen der beiden zeitgleich dargebotenen Stimuli (Abbildung 2).

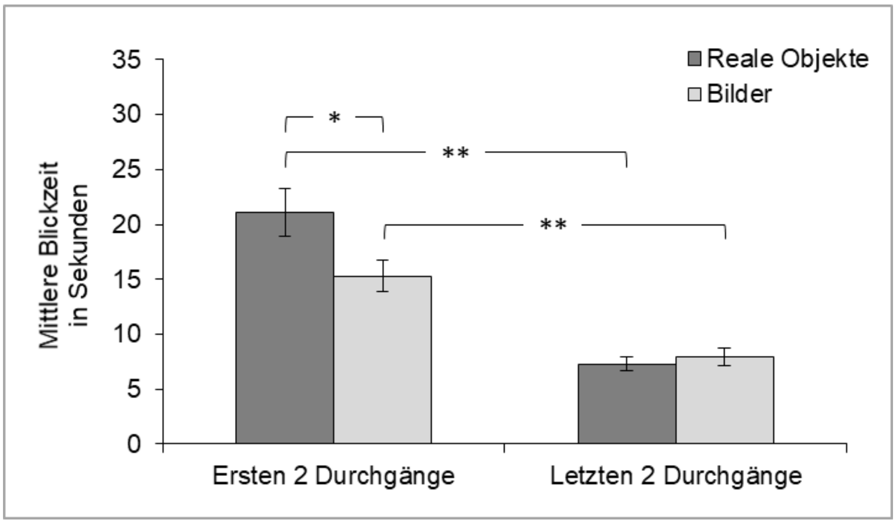

Abbildung 1. Mittlere Blickzeiten für reale Objekte und Bilder während der ersten beiden und letzten beiden Habituationsdurchgänge. Die Fehlerbalken geben den Standardfehler des Mittelwerts an. *Anmerkung*. * *p* < .05, ** *p* < .001.

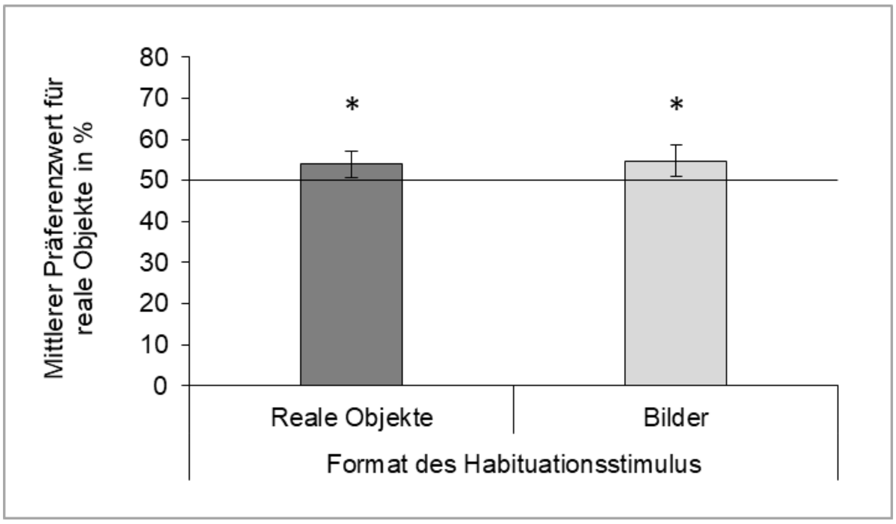

Abbildung 2. Mittlere prozentuale Blickzuwendung auf reale Objekte in Abhängigkeit des in der Habituation dargebotenen Stimulusformats. Die Fehlerbalken geben die 97,5% Konfidenzintervalle an. *Anmerkung*. * *p* < .01.

Insgesamt verdeutlicht Studie 1a für Säuglinge ab 7 Monaten erstmals Unterschiede in der visuellen Verarbeitung von realen Objekten und ihren Abbildungen im Sinne eines Real-object advantage. Zu Beginn der visuellen Habituation war die Aufmerksamkeitszuwendung für die realen Objekte bereits stärker ausgeprägt. Diese setzte sich über die Habituation hinaus fort, sodass auch bei simultaner Darbietung die realen Objekte länger betrachtet wurden. Mit Blick auf die Säuglingen, die zuvor bereits an reale Objekte habituiert worden waren lässt sich schlussfolgern, dass reale Objekte sowohl neuronal (Snow et al., 2011) als auch visuell stärker ansprechen und so eine effizientere oder auch ausgedehntere Verarbeitung induzieren.

2.2 Studie 1b – Manual exploration of objects is related to 7-month-old infants' visual preference for real objects (Gerhard, Culham & Schwarzer, eingereicht)

Die Ergebnisse aus Studie 1a demonstrieren, dass Säuglinge ab 7 Monaten bevorzugt reale Objekte betrachten, wenn ihnen diese zeitgleich mit Bildern der Objekte dargeboten werden. Dieser Befund wird durch vergangene Untersuchungen gestützt, die ebenfalls zeigen, dass realen Objekten auf visueller und motorischer Ebene eine stärkere Aufmerksamkeit zuteilwird als ihren bildhaften Entsprechungen (DeLoache, Pierroutsakos, Uttal, Rosengren & Gottlieb, 1998; DeLoache, Strauss & Maynard, 1979). Die Wahrnehmungsentwicklung von Objektmerkmalen ist dabei in besonderer Weise mit Erfahrungen gekoppelt, die durch motorische Aktivität mit Objekten gewonnen werden (z.B. Libertus & Hauf, 2017). Soska und Kollegen (2010) konnten in diesem Zusammenhang explizit zeigen, dass das visuell-manuelle Objektexplorationsverhalten von Säuglingen positiv mit der Wahrnehmung der drei-dimensionalen Struktur von Objekten assoziiert ist. Auch das Erkennen spezifischer Affordanzen bei Objekten mit Merkmalsunterschieden in Farbe, Größe und Form, steht mit den manuellen Handlungen gegenüber diesen Objekten in Zusammenhang (Montesano, Lopes, Bernardino & Santos-Victor, 2008). Bisher nicht untersucht ist, inwiefern sich Unterschiede im manuellen Objektexplorationsverhalten auch auf die spontane visuelle Aufmerksamkeits-zuwendung für reale Objekte und deren Abbildungen auswirken. Studie 1b widmete sich daher der Untersuchung dieses Zusammenhangs bei Säuglingen im ersten Lebensjahr.

Unter Verwendung eines visuellen Präferenzparadigmas wurden 7 Monate alten Säuglingen Objektpaare simultan dargeboten, die aus einem realen Spielzeug und dessen fotorealistischer Abbildung bestanden (vgl. Testphase aus Studie 1a). Erfasst wurden die Blickzeiten der Säuglinge auf die präsentierten Objekte, mittels derer prozentuale Blick-präferenzwerte für das jeweilig präsentierte reale und bildhafte Objekt berechnet wurden. Zudem durchlief jeder Säugling, in Anlehnung an das Vorgehen von Soska und Kollegn (2010), eine Objektexplorationsaufgabe, mit der die Fertigkeiten in der spontanen, visuell gesteuerten manuellen Exploration von Objekten gemessen werden. Innerhalb der Explorationsaufgabe durften die Säuglinge nacheinander 5 Spielzeugobjekte für eine feste Zeitspanne von jeweils

40 Sekunden frei mit den Händen erkunden. Mit Berücksichtigung des gezeigten Verhaltens der Säuglinge während der visuell-manuellen Objektexploration, lieferten die Ergebnisse bedeutsame Hinweise für einen Einfluss von sogenannten *Fingerings* auf die spontane visuelle Präferenz für reale Objekte und deren Abbildungen (Abbildung 3). Fingerings bezeichnen das Abfahren von Objektoberflächen und –kanten mit einem oder mehreren Fingern. Säuglinge, die im Rahmen der Objektexplorationsaufgabe als hoch explorativ in dieser Explorationshandlung eingestuft wurden, schauten während der visuellen Präferenzaufgabe bedeutsam länger auf das reale gegenüber dem bildhaften Objekt. Säuglinge, die hingegen als wenig explorativ eingestuft wurden, betrachteten beide Objektformate gleich lange. Darüber hinaus zeigte sich, unabhängig vom Explorationsverhalten der Säuglinge, eine übergreifende visuelle Präferenz für reale Objekte. Dieser Befund stellt eine Replikation der visuellen Präferenz für reale Objekte aus dem visuellen Paarvergleich in Studie 1a dar (vgl. Abbildung 2).

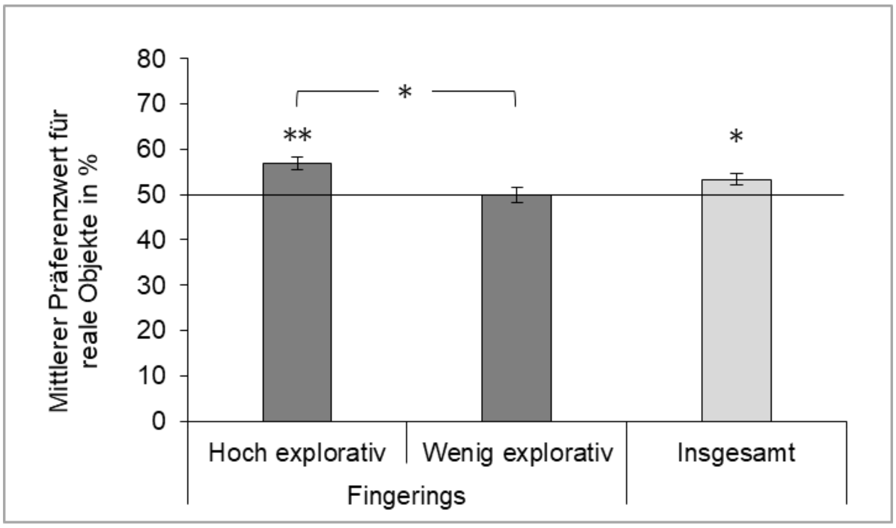

Abbildung 3. Mittlere prozentuale Blickzuwendung auf reale Objekte für Säuglinge mit einem hohen und einem niedrigen Wert in Fingerings und für die Gesamtstichprobe. Die Fehlerbalken geben den Standardfehler des Mittelwerts an. *Anmerkung*. * $p < .01$, ** $p < .001$.

Die Befunde aus Studie 1b demonstrieren, dass der Zusammenhang zwischen spontaner Aufmerksamkeitszuwendung und Objektformat bei 7-monatigen Säuglingen maßgeblich durch ihre Erfahrungen mit bestimmten manuellen Objektexplorationshandlungen beeinflusst wird. Erfahrungen in der Ausführung von Fingerings sind dabei in besonderer Weise mit einer visuellen Präferenz für reale Objekte assoziiert, möglicherweise, weil im Rahmen ihrer Ausführung die Fingerspitzen als sensitivste Stelle der Hand mit Objekten in Kontakt kommen. Auf diese Weise wird eine ausgesprochen feine haptische Erfassung der Objekte ermöglicht (Rochat, 1989), welche mit der Extraktion spezifischer Informationen hinsichtlich der Form und Struktur von Objekten assoziiert ist (Lederman & Klatzky, 1987, 1993). Dies bestätigt außerdem, dass haptische Aktivitäten mit der Erfassung objektspezifischer Affordanzen in Verbindung zu stehen scheinen (Montesano et al., 2008).

3. Studie 2 – Impact of rotation angle on crawling and non-crawling 9-month-old infants' mental rotation ability (Gerhard & Schwarzer, 2018)

Die Fähigkeit Objekte mental zu repräsentieren und uns ihre Transformation im Raum vorzustellen ist im Rahmen der Planung von Handlungen und der Antizipation ihrer Konsequenzen bereits im frühen Säuglingsalter hoch relevant. Einen solch bedeutsamen und daher vielfach untersuchten mentalen Transformationsprozess aus dem Bereich der Inner-Objekt Beziehungen stellt die mentale Rotation dar. Sie bezeichnet die Fähigkeit zur geistigen Simulation der Drehbewegung von zwei- und dreidimensionalen Objekten im Raum (Linn & Petersen, 1985) und wird von Säuglingen zum Beispiel für die Erkennung oder das Ergreifen bewegter Objekte benötigt (Schwarzer, Freitag, Buckel, et al., 2013). Den Nachweis, dass der Erkennung von in ihrer Orientierung veränderten Objekten ein Prozess der mentalen Rotation zugrunde liegt, erbrachten erstmals Shepard and Metzler (1971) bei Erwachsenen. Sie zeigten, dass bei linear zunehmender Orientierungsabweichung zweier gegeneinander rotierter Objekte, die Reaktionszeiten bezüglich einer Entscheidung über die Gleichheit dieser Objekte (Spiegel-objekt vs. gleiches Objekt) proportional anstiegen. Die Autoren schlussfolgerten, dass die Probanden versucht haben müssen die Objekte mittels interner Rotation in Übereinstimmung zu bringen. Anschlussuntersuchungen lieferten auf der Basis dieses Befunds nähere Belege, dass mentale Rotationsvorgänge analog zu realen Rotationen in der Wirklichkeit ablaufen, sich in dem linearen Zusammenhang von Reaktionszeit und Rotationswinkel also die physikalischen Gesetze der Außenwelt widerspiegeln (s. Cooper & Shepard, 1973). Entwicklungs-psychologisch sind die Ursprünge mentaler Rotationsprozesse bereits bei Säuglingen von unter 6 Monaten beforscht worden (Hespos & Rochat, 1997; Moore & Johnson, 2008, 2011, Quinn & Liben, 2008, 2014; Rochat & Hespos, 1996). Belegt ist ihr Erstauftreten für ein Alter von ungefähr 3-4 Monaten (Moore & Johnson, 2011; Quinn & Liben, 2008, 2014). Bislang existierte allerdings nahezu keine Studie, die sich dem spezifischen Einfluss unterschiedlich großer Rotationswinkel auf die mentale Rotation im Säuglingsalter widmete und somit einen tieferen Einblick in dessen mögliche analoge Natur für diesen Altersbereich gewährt hätte. Bereits gut belegt sind hingegen die positiven Effekte selbstinduzierter Fortbewegungs-erfahrungen für die mentale Objektrotation im Säuglingsalter (Frick & Möhring, 2013; Schwarzer, Freitag, Buckel, et al., 2013; Schwarzer, Freitag & Schum, 2013). Studie 2 untersuchte daher erstmals den Einfluss unterschiedlich großer Rotationswinkel auf die mentale Rotationsfähigkeit von Säuglingen mit und ohne Erfahrungen in der selbstinduzierten Fortbewegungsform des Krabbelns auf Händen und Knien.

Unter Verwendung eine Habituations-Dishabituations-Paradigmas, wurden 9 Monate alte Säuglinge zunächst an ein Video eines um 180° rotierenden Shepard-Metzler Objekts habituiert. In der anschließenden Testphase sahen die Säuglinge, in einer von zwei möglichen Testbedingungen, das bereits bekannte Habituationsobjekt und dessen unbekannte Spiegelvariante nacheinander in einem neuen Winkel um 90° rotieren. Der entscheidende Unterschied zwischen den beiden Testbedingungen lag in dem Ausmaß der für die Wiedererkennung des bereits bekannten Testobjekts auszuführenden mentalen Objektrotation. Während sich die Rotation der Testobjekte in Bedingung 1 direkt an das Ende der Rotation des Habituationsobjekts anschloss (0°-Bedingung), begannen die Rotationen der Testobjekte in Bedingung 2 um 54° versetzt (54°-Bedingung; s. Abbildung 4).

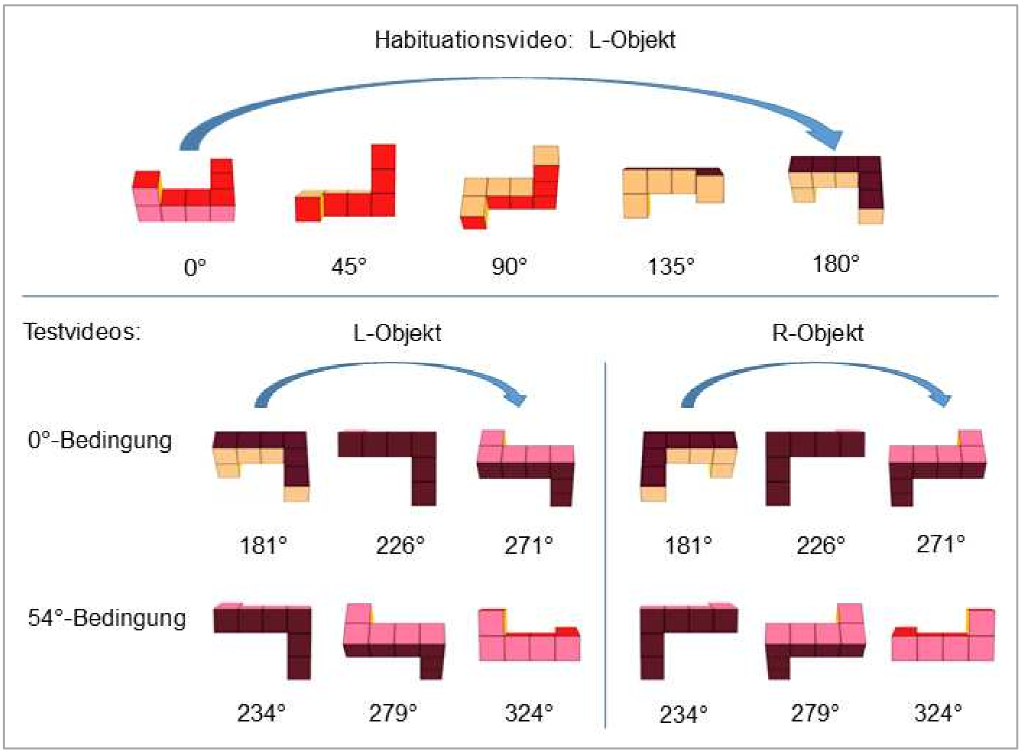

Abbildung 4. Beispielhafte Darstellung der Objekte aus den Habituations- und Testvideos. Die Objekte in den Habituationsvideos rotierten wiederholt vorwärts durch 180°. In beiden Testbedingungen rotierten die Objekte wiederholt vorwärts durch 90°.

Erfasst wurden die Blickzeiten der Säuglinge auf die jeweils präsentierten Objekte, die für die Analyse des Blickverhaltens während der Testphase in prozentuale Blickpräferenzwerte überführt wurden. Die Erfahrung im Krabbeln auf Händen und Knien wurde mittels Befragung der Eltern während der Testung erhoben. In Abbildung 5 sind die Ergebnisse der mentalen Rotationsaufgabe graphisch aufbereitet. Der Einfluss der unterschiedlichen mentalen Rotationsanforderungen in den beiden Testbedingungen (0° vs. 54°) stellt sich hier als abhängig von den Krabbelerfahrungen der Säuglinge dar (Interaktion: $p < .01$). Die Nichtkrabbler zeigten in beiden Testbedingungen keine bedeutsamen Blickpräferenzen und somit auch keine Anzeichen für das Ausführen mentaler Rotationsvorgänge während der Aufgabe. Im Gegensatz dazu fanden sich entsprechende Belege für die krabbelnden Säuglinge. Krabbler in der 0°-Bedingung schauten länger auf das neue Spiegelobjekt, Krabbler in der 54°-Bedingung hingegen länger auf das bekannte Habituationsobjekt in der neuen Rotation. Während das Auftreten dieser bedeutsamen Blickpräferenzen in beiden Testbedingungen jeweils auf ein Vorkommen mentaler Rotationsprozesse innerhalb der Krabbler hinweist, deutet ihre unterschiedliche Richtung (Neuheit vs. Bekanntheit) auf einen spezifischen Einfluss des Ausmaß der auszuführenden mentalen Rotation hin. Diese schien für Krabbler in der 0°-Bedingung bedeutsam leichter zu sein, als für Krabbler in der 54°-Bedingung.

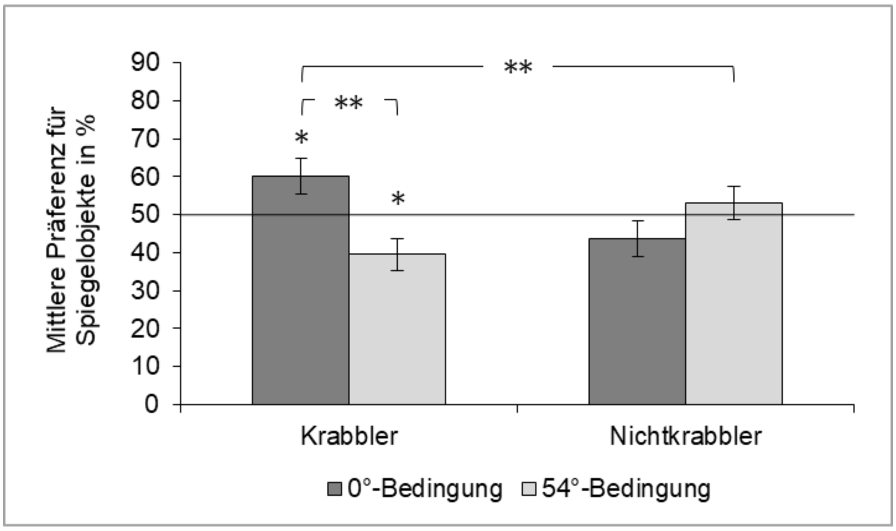

Abbildung 5. Mittlere prozentuale Blickzuwendung auf das Spiegelobjekt in der 0°- und 54°-Bedingung getrennt aufgeführt für Krabbler und Nichtkrabbler. Die Fehlerbalken geben den Standardfehler des Mittelwerts an. *Anmerkung*. * $p < .05$, ** $p < .01$.

Studie 2 liefert somit erste Belege dafür, dass der Prozess der mentale Rotation bei Säuglingen ab 9 Monaten ebenfalls analoger Natur sein könnte und demnach vergleichbar zu Objektrotationen in der realen Welt abläuft (vgl. Cooper & Shepard, 1973; Shepard & Metzler, 1971). Darüber hinaus stärkt sie für das Säuglingsalter den positiven Zusammenhang zwischen motorischen Erfahrungen über selbstinduzierte Fortbewegung und den Leistungen bei geistigen Objekttransformationsprozessen wie der mentalen Rotation.

4. Diskussion

Das Anliegen der vorliegenden Arbeit war, einen erweiternden Einblick in zwei visuell-räumliche Objektwahrnehmungsprozesse aus dem Bereich der Inner-Objekt Beziehungen im Säuglingsalter zu gewähren: (1) In die visuelle Wahrnehmung von realen Objekten und Bildern dieser Objekte und (2) in die mentale Rotationsfähigkeit. Auf diese Weise sollte eine weiterführende Einschätzung gelingen, inwiefern bereits Säuglinge im ersten Lebensjahr einen Real-object advantage aufweisen, der Einsatz bildhafter Objekte als Repräsentationen realer Objekte also möglicherweise zu differentiellen Wahrnehmungseffekten führt. Zum anderen ging es darum tiefergehend zu verstehen, inwiefern der Prozess der mentalen Rotation im Säuglingsalter äquivalent zur analogen mentalen Rotation bei Erwachsenen abläuft. Nicht zuletzt fokussierte die Arbeit darauf, den Einfluss räumlicher Objekterfahrungen, durch fein- sowie grobmotorische Prozesse, in ihrer Rolle als Motoren der Entwicklung kindlicher Wahrnehmung und Kognition innerhalb beider Fähigkeitsbereiche zu beleuchten.

Studie 1a (Gerhard et al., 2016) demonstrierte, dass die visuelle Objektverarbeitung bei Säuglingen ab 7 Monaten durch das Format beeinflusst wird, indem ihnen Objekte präsentiert werden. Die Einflussnahme erfolgte in Form einer effizienteren Verarbeitung realer Objekte im Gegensatz zu ihren bildhaften Entsprechungen. Die spiegelte sich in einem stärker ausgeprägten Habituationsmuster für Säuglinge wider, die an ein reales Objekt habituiert wurden. Die übergreifende visuelle Präferenz für reale Objekte bei simultaner Darbietung beider Objektformate verweist außerdem auf eine spontan erhöhte Aufmerksamkeit für reale Objekte gegenüber Bildern der Objekte. Diese kann als Ausgangspunkt für eine effizientere oder auch ausgedehntere Verarbeitung realer Objekte interpretiert werden.

Studie 1b (Gerhard et al., eingereicht) stützt den Befund einer stärkeren Aufmerksamkeit für reale Objekte gegenüber Bildern und konnte in der Folge belegen, dass sie bei 7-monatigen Säuglingen mit der visuell gesteuerten manuellen Exploration von Objekten zusammenhängt. Das Abfahren von Alltagsobjekten mit den Fingern förderte hier die Ausrichtung der Aufmerksamkeit auf reale Objekte und lässt den Schluss zu, dass derartige Explorationshandlungen Lernerfahrungen hinsichtlich Objektmerkmalen wie ihrer räumlichen Tiefenstruktur und der damit einhergehenden Affordanz bereitstellen.

Studie 2 (Gerhard & Schwarzer, 2018) lieferte erste Evidenz, dass die Qualität des mentalen Rotationsprozesses bei 9-monatigen Säuglingen mit ihren Erfahrungen in der selbstinduzierten Fortbewegungsform des Krabbelns auf Händen und Knien zusammenhängt. Für krabbelnde Säuglinge fanden sich erste Hinweise auf einen ähnlichen Vorgang der analogen mentalen Rotation wie bei Erwachsenen. Indiz hierfür war, dass die mentale Rotationsleistung der krabbelnden Säuglinge durch eine Erhöhung des mental auszuführenden Rotationswinkels beeinträchtigt wurde. Die nicht krabbelnden Säuglinge zeigten in dieser Aufgabe keine Hinweise auf mentale Rotation, was zusätzlich die Bedeutsamkeit der selbstinduzierten Fortbewegung für die Entwicklung der mentalen Rotationsfähigkeit betont.

4.1 Empirische und theoretische Einordnung der Ergebnisse

Die Erkenntnisse der vorliegenden Arbeit stehen in Einklang mit einer Reihe an empirischen Vorbefunden. Studie 1a demonstrierte erstmalig für Säuglinge im ersten Lebensjahr eine effizientere oder auch ausgedehntere visuelle Verarbeitung realer Objekte gegenüber Bildern. Dieser Effekt korrespondiert mit der Arbeit von Snow und Kollegen (2011), die auf eine ausgedehntere neuronale Verarbeitung visuell präsentierter realer Objekte im Vergleich zu ihren Abbildungen verweist. Es ist anzunehmen, dass reale Objekte aufgrund ihrer effizienteren Verarbeitung besser mental repräsentiert werden. In diese Richtung interpretiert werden kann die vergleichsweise stärkere Reduktion der Blickzuwendung während der Habituation an reale Objekte (vgl. Singh et al., 2015). In der Tat lassen verschiedene Studien Leistungsdifferenzen in übergeordneten kognitiven Prozessen erkennen, die vermutlich auf Basis qualitativ distinkter mentaler Repräsentationen von realen Objekten und Bildern einzuordnen sind. So gelingt die Erkennung realer Objekte besser bei Patienten mit visueller Objektagnosie (Chainay & Humphreys, 2001; Humphrey et al., 1994; Riddoch & Humphreys, 1987; Servos et al., 1993) und auf kortikaler Ebene bereits schneller im Kleinkindalter (Carver et al., 2006). Weiter gestützt wird dieser Befund von Snow et al. (2014), die einen direkten Vergleich der Gedächtnisleistung und damit des Wiederabrufs mentaler Repräsentationen von realen Objekten und Bildern der Objekte vornahmen. Sie konnten den Vorteil realer Objekte bestätigen. Dass der Einsatz realitätsnaher Stimuli zu Leistungsvorteilen in Fähigkeiten aus dem Bereich der Zwischen-, vor allem aber der Inner-Objekt Beziehungen führen kann, wurde vereinzelt angedeutet. Es zeigte sich beispielsweise, dass die visuell-räumlichen Prädiktionsfähigkeiten von Säuglingen durch die Verwendung drei- statt zweidimensionaler Stimuli verbessert werden können (Johnson et al., 2012; Woods, Wilcox, Armstrong & Alexander, 2010). Mehr noch profitieren mentale Rotationsleistungen (Felix, Parker, Lee & Gabriel, 2011) und korrespondierende Trainingseffekte (Moreau, 2013), wenn erwachsenen Probanden reale oder virtuelle, dreidimensionale Objekte präsentiert werden. Studie 1a demonstrierte zudem, dass die untersuchten Säuglinge realen Objekten bei gleichzeitiger Präsentation mit ihren Abbildungen mehr Aufmerksamkeit schenkten, selbst wenn ihnen das Objekt aus der Habituation bereits bekannt war. Dieser Befund bestärkt und steht in Einklang mit einigen wenigen Studien, die sowohl Blick- als auch Greifpräferenzen für reale Objekte gegenüber Bildern in der Abwesenheit von vorgeschalteten Habituationsvorgängen fanden (DeLoache et al., 1998, 1979). Er kann außerdem als mögliche Grundlage für die effizientere oder auch ausgedehntere Verarbeitung realer Objekte gesehen werden, zumal die Aufmerksamkeit gegenüber den realen Objekten bereits zu Beginn der Habituationsphase ausgeprägter war.

Studie 1b liefert im Kontext der Befunde aus Studie 1a erstmalig Hinweise dafür, dass der Real-object advantage in der Aufmerksamkeitszuwendung mit den Erfahrungen der Säuglinge in der visuell gesteuerten manuellen Exploration von Objekten zusammenhängt. Damit fügt sie sich ein in empirische Arbeiten, die eine positive Verbindung zwischen feinmotorischen Fertigkeiten und der Verarbeitung von Inner-Objekt Beziehungen im Säuglingsalter belegen. Manuelles Explorationsverhalten steht beispielweise in förderlichem Zusammenhang zur mentalen Rotationsfähigkeit (Möhring & Frick, 2013; Schwarzer, Freitag & Schum, 2013) und, für Studie 1b besonders relevant, zur Wahrnehmung der dreidimensionalen Struktur von Objekten (Soska et al., 2010). Ansätze zur Modellierung von Interaktionskompetenzen bei sozialen Robotern zeigen zudem, dass das Erlernen von Objektaffordanzen einer Koordination von perzeptuellen und manuellen Handlungsprozessen bedarf (Montesano et al., 2008). Es sind diese Unterschiede zwischen realen Objekten und Bildern hinsichtlich der Bereitstellung an Tiefeninformationen und an Affordanzen, die als zugrundeliegende Faktoren für verschiedene perzeptuelle und kognitive Leistungsdifferenzen diskutiert werden (Snow et al., 2011, 2014) und deren Wahrnehmung wiederum mit motorischen Fertigkeiten assoziiert zu sein scheint.

Schließlich reiht sich auch Studie 2 in die bisherige Ergebnislage einer positiven Verbindung von Motorik und visuell-räumlicher Objektwahrnehmung ein. Sie demonstrierte, dass die Qualität der mentalen Rotation bei 9-monatigen Säuglingen von ihren grobmotorischen Erfahrungen im selbstinduzierten Krabbeln auf Händen und Knien profitiert. Dieses Ergebnis korrespondiert mit bisherigen Studien, die für die Entwicklung der mentalen Rotationsfähigkeit im Säuglingsalter spezifische Zusammenhänge mit den selbstinduzierten Fortbewegungsformen des Krabbelns und des Gehens mit Hilfestellung aufzeigen (Frick & Möhring, 2013; Schwarzer, Freitag, Buckel, et al., 2013; Schwarzer, Freitag & Schum, 2013). Außerdem stehen sie in Einklang mit bildgebenden Arbeiten, die ähnliche neuronale Aktivierungsmuster während motorischen und mentalen Rotationsprozessen belegen (Richter et al., 2000; Zacks, 2008). Studie 2 erweitert zudem die aktuelle Befundlage zur Entwicklung der mentalen Rotationsfähigkeit, da sie für das Säuglingsalter erstmals einen qualitativ ähnlichen Prozess der analogen mentale Rotation wie bei Erwachsenen beschreibt. Die mentale Rotationsleistung der krabbelnden Säuglinge zeigte sich abhängig vom Ausmaß der mental auszuführenden

Objektrotation, sodass bei Vergrößerung des Rotationswinkels ein Leistungsabfall von einer Neuigkeits- hin zu einer Bekanntheitspräferenz zu beobachten war. Es kann daher vermutet werden, dass die Ausführung der mentalen Rotation bei erhöhtem Rotationswinkel anspruchsvoller war (Rose et al., 1982). Vergleichbare Einflüsse ansteigender Rotationswinkel demonstrierten erstmals Shepard und Metzler (1971) in einer Stichprobe mit Erwachsenen. Die Reaktionszeiten der Probanden als Leistungsindikator in einer mentalen Rotationsaufgabe stiegen in ihrer Studie proportional zum zunehmenden Rotationswinkel an. Über Anschlussuntersuchungen kamen die Forscher letztlich zu dem Schluss, dass erwachsene Personen für die Identifikation von in ihrer räumlichen Orientierung veränderten Objekten mentale Rotation ausführen (z.B. Cooper & Shepard, 1973). Außerdem schlussfolgerten sie, dass dieser Prozess analog zu realen Rotationen in der Wirklichkeit ablaufen müsse, da beide den Gesetzten von Zeit und Raum folgen, das heißt mehr Zeit für größere Winkelrotationen beanspruchen. Studie 2 deutet erstmals an, dass diese Schlussfolgerungen auch auf 9 Monate alte, erfahrene Krabbler zutreffen könnten.

Studie 1b und Studie 2 bestätigen jedoch nicht nur empirische Arbeiten zum Zusammenhang von visuell-räumlichen Objektwahrnehmungskompetenzen und Motorik. Sie stehen auch in Einklang mit traditionellen und modernen theoretischen Ansätzen über die kindliche Entwicklung von Wahrnehmung und Kognition. Bereits Piaget (1952) ging davon aus, dass durch sensomotorische Explorationsvorgänge kognitive Entwicklungsprozesse zum Verständnis der physikalischen, dreidimensionalen Welt in Gang gesetzt werden. Solche Explorationsvorgänge werden auch durch die Entwicklung der selbstinduzierten Fortbewegung zunehmend bereitgestellt. Campos und Kollegen (2000) betonen sie daher als wichtigen Faktor für die Entwicklung von Wahrnehmung und Kognition innerhalb ihres Ansatzes Travel broadens the mind. Die Erkenntnisse aus Studie 2 unterstützen diese Auffassung, indem sie einen positiven Zusammenhang zwischen der kognitiven Fähigkeit zur mentalen Objektrotation und dem Krabbeln auf Händen und Knien aufzeigen. Außerdem fügen sie sich ein in die theoretische Perspektive der Embodied cognition, die kognitiven Fortschritt gleichsam als Ergebnis sensomotorischer Aktivität mit der Umgebung versteht (Smith & Gasser, 2005; Thelen, 2000). Die Befunde, vor allem aus Studie 1b, korrespondieren nicht zuletzt mit der ökologischen Theorie der Wahrnehmungsentwicklung nach Eleanor Gibson (z.B. Gibson, 1988). Die verstärkte Aufmerksamkeit für reale Objekte gegenüber Bildern bei Säuglingen mit einer feineren haptischen Erfassung von Objektmerkmalen stützt die Auffassung Gibsons, dass Wahrnehmung ein aktiver Prozess ist, der im Dienst von Handlungen und der Entdeckung von Handlungsmöglichkeiten steht. Gemeinsam ist diesen Ansätzen letztlich, dass sie Motorik als *enabling* begreifen (Adolph & Hoch, im Druck). Motorische Prozesse werden als wichtiger Ausgangspunkt für die Bereitstellung neuer Lernmöglichkeiten über Objekte, Ereignisse oder Personen verstanden (Thelen, 2000). Auf diese Weise führen sie zu Verbesserungen in einem weiten Spektrum an psychologischen Fähigkeiten, wie der Sprache (He et al., 2015; Libertus & Violi, 2016; Walle & Campos, 2013) oder sozialen und emotionalen Fähigkeiten (Campos et al., 1992; Karasik et al., 2016; Walle, 2016). Sie führen aber auch zu Leistungszuwächsen in der Verarbeitung visuell-räumlicher Objektinformationen aus dem Bereich der Inner-Objekt Beziehungen, wie Studie 1b und Studie 2 belegen.

4.2 Implikationen für zukünftige Forschung

Die Studien der vorliegenden Arbeit bieten neue Erkenntnisse zur Wahrnehmung von Objekten unterschiedlichen Darstellungsformats und zur mentalen Rotationsfähigkeit im Säuglingsalter. Sie geben jedoch auch Anlass zu weiterer Forschung. Der Befund aus Studie 1a hinsichtlich einer distinkten visuellen Verarbeitung von realen Objekten und ihren Abbildungen im ersten Lebensjahr wirft die Frage auf, ob dieser Effekt auch neuronal abbildbar ist und inwiefern er sich äquivalent zu den distinkten neuronalen Verarbeitungsmechanismen im Erwachsenengehirn zeigt (Snow et al., 2011). Das bildgebende Verfahren der funktionellen Nahinfrarotspektroskopie (fNIRS) eröffnet hierfür neue Annäherungsmöglichkeiten. Es erlaubt die Untersuchung der neuronalen Verankerung wahrnehmungsbezogener, kognitiver und sozialer Verarbeitungsprozesse erstmals in wachen und beteiligten Säuglingen (Wilcox & Biondi, 2015b), auch über die Erfassung von Effekten der Wiederholungsunterdrückung (z.B. Kobayashi et al., 2011).

Studie 1a verweist jedoch nicht nur auf einen Real-object advantage in der visuellen Verarbeitung von Objekten ungleichen Formats. Zusammen mit Studie 1b verdeutlicht sie, dass reale Objekte eine stärkere visuelle Aufmerksamkeitszuwendung induzieren als ihre bildhaften Entsprechungen. Mögliche Gründe hierfür betreffen die Unterschiede in der Reichhaltigkeit an visuellen Tiefeninformationen, durch binokularer Disparität und Bewegungsparallaxe, sowie an handlungsrelevanten Affordanzen (z.B. Snow et al., 2014). Zukünftigen Studien obliegt es, eine genauere Einschätzung über die Beiträge dieser Merkmalsunterschiede für den Real-object advantage im Säuglingsalter zu treffen. Hierfür könnte man Säuglingen die Objekte unter monokularen Bedingungen präsentieren, sodass die Verfügbarkeit binokularer Tiefen-informationen im Fall der realen Objekte eliminiert wäre. Auf Basis des gleichen Prinzips ließe sich der Einfluss kinetischer Tiefenhinweise durch Bewegungsparallaxe abschätzen. Dazu notwendig wäre eine räumliche Konstanthaltung des optischen Eindrucks der präsentierten realen Objekte. Dies bedarf einer Kontrolle von Kopfbewegungen oder einer virtuellen Darstellung, bei welcher der optische Eindruck trotz Kopfbewegungen unverändert bleibt. In letzterem Fall wäre allerdings der Einsatz realer Objekte nicht möglich und somit auch kein direkter Vergleich zwischen realen Objekten und Bildern. Die Bedeutung von Unterschieden in der Affordanz als Hintergrund für den Real-object advantage könnte näher betrachtet werden, indem man verschiedenen Gruppen an Säuglingen unterschiedliche Intensitäten an entweder Handlungserfahrungen oder rein visuellen Erfahrungen mit realen Objekten bietet und beobachtet, wie sich dies auf die Verarbeitung von und die Präferenz für reale Objekte auswirkt.

Studie 2 veranschaulichte erstmals, dass sich der Prozess der mentalen Rotation bei 9 Monate alten, krabbelnden Säuglingen, den analogen mentalen Rotationsvorgängen bei Erwachsenen anzunähern scheint. Der Rückschluss auf kognitive Mechanismen über den Vergleich von Blickzeiten mit Reaktionszeiten ist allerdings nur eingeschränkt möglich (Frick et al., 2014; Newcombe & Frick, 2010). Weitere Schritte zur Spezifikation des Prozesses der mentalen Rotation bei Säuglingen sind daher nötig. Auch hier kann die Identifikation neuronaler Übereinstimmungen hilfreich sein. Elektrophysiologische aber auch funktionelle Bildgebungsstudien zeigen charakteristische Aktivierungen in Regionen des Parietalkortex und des prämotorischen Kortex während mentalen Rotationsvorgängen bei Erwachsenen, die mit der Größe der auszuführenden Rotation zunehmen (Gogos et al., 2010; Heil, 2002; Peronnet & Farah, 1989; Podzebenko, Egan & Watson, 2002; Richter et al., 2000). Mittels EEG und fNIRS könnte näher analysiert werden, ob und inwiefern die neuronalen Aktivierungsmuster zwischen Säuglingen und Erwachsenen in mentalen Rotationsaufgaben korrespondieren und zwischen krabbelnden und nicht krabbelnden Säuglingen möglicherweise divergieren.

Nicht zuletzt ist Gegenstand zukünftiger Forschung die intensivere Betrachtung der vermittelnden Prozesse zwischen motorischen Fertigkeiten und wahrnehmungsbezogenen sowie kognitiven Fähigkeiten. Im Kontext räumlicher Fähigkeiten gilt als ein vielversprechender Kandidat die spezifischere und vermehrte Enkodierung visuell-räumlicher Informationen durch eine aktive, selbstinduzierte Generierung dieser Informationen (Acredolo, Adams & Goodwyn, 1984; Antrilli & Wang, 2016; Kretch, Franchak & Adolph, 2014). Die Möglichkeit räumliche Informationen selbst zu generieren ist bei Säuglingen mit weiter entwickelten motorischen Fertigkeiten entsprechend stärker ausgeprägt, wodurch sich unterschiedliche Leistungen in visuell-räumlichen Fähigkeiten, wie etwa der mentalen Rotation (z.B. Frick & Möhring, 2013; Schwarzer, Freitag & Schum, 2013), erklären ließen. Aufgabe ist es genauer zu identifizieren, welche Informationen, die während manuellen Explorationshandlungen erzeugt werden, den Säuglingen bei der Bearbeitung visuell-räumlicher Aufgaben helfen und wie sich die Enkodierungsmuster visuell-räumlicher Informationen mit zunehmenden Fortbewegungserfahrungen (z.B. im Krabbeln) verändern.

4.3 Schlussfolgerungen

Zusammengefasst verdeutlichen die Studienergebnisse, dass Säuglinge bereits im ersten Lebensjahr einen Real-object advantage ausbilden (Studie 1a und Studie 1b). Die Verwendung bildhafter Objektstimuli als ökologisch valide Repräsentationen realer Objekte in der entwicklungspsychologischen Erforschung von Wahrnehmung und Kognition ist daher kritisch zu sehen. Entsprechende Forschungsansätze sollten zukünftig vermehrt den Einsatz realer oder zumindest virtueller Stimuli anstreben, um eine Unterschätzung des Fähigkeitsstandes der Säuglinge zu vermeiden. Die vorliegende Arbeit zeigt außerdem, dass die Entwicklung motorischer Fertigkeiten, wie der manuellen Objektexploration und der selbstinduzierten Fortbewegung, für das sich ausbildende Verständnis der dreidimensionalen Natur (Studie 1b) und der räumlichen Orientierung von Objekten (Studie 2) förderlich ist. Aufgrund der Bedeutung dieser Fähigkeiten für die alltägliche Anpassung des Individuums an seine Umwelt sowie für akademischen Leistungsentwicklungen (z.B. Newcombe et al., 2013), sollte der entwicklungsgerechten Ausbildung motorischer Fertigkeiten daher besondere Beachtung geschenkt werden.

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6. Übersicht

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Distinct Visual Processing of Real Objects and Pictures of Those Objects in 7- to 9-month-old Infants

Theresa M. Gerhard[1]*, *Jody C. Culham*[2,3] *and Gudrun Schwarzer*[1]

[1] *Department of Developmental Psychology, Faculty of Psychology and Sports Science, Justus-Liebig-University Giessen, Giessen, Germany,* [2] *Department of Psychology, Brain and Mind Institute, The University of Western Ontario, London, ON, Canada,* [3] *Centre for Mind/Brain Sciences, University of Trento, Mattarello, Italy*

The present study examined 7- and 9-month-old infants' visual habituation to real objects and pictures of the same objects and their preferences between real and pictorial versions of the same objects following habituation. Different hypotheses would predict that infants may habituate faster to pictures than real objects (based on proposed theoretical links between behavioral habituation in infants and neuroimaging adaptation in adults) or to real objects vs. pictures (based on past infant electrophysiology data). Sixty-one 7-month-old infants and fifty-nine 9-month-old infants were habituated to either a real object or a picture of the same object and afterward preference tested with the habituation object paired with either the novel real object or its picture counterpart. Infants of both age groups showed basic information-processing advantages for real objects. Specifically, during the initial presentations, 9-month-old infants looked longer at stimuli in both formats than the 7-month olds but more importantly both age groups looked longer at real objects than pictures, though with repeated presentations, they habituated faster for real objects such that at the end of habituation, they looked equally at both types of stimuli. Surprisingly, even after habituation, infants preferred to look at the real objects, regardless of whether they had habituated to photos or real objects. Our findings suggest that from as early as 7-months of age, infants show strong preferences for real objects, perhaps because real objects are visually richer and/or enable the potential for genuine interactions.

Keywords: object processing, visual habituation, real objects, pictures, infants

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Tzvi Ganel,
Ben-Gurion University of the Negev, Israel
Kristine Ann Kovack-Lesh,
Ripon College, USA

Correspondence:
Theresa M. Gerhard
theresa.gerhard@psychol.uni-giessen.de

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INTRODUCTION

Recent research on human object perception and recognition has increasingly questioned the ecological validity of using pictures of objects (such as photos or line drawings) as a proxy for real objects (Snow et al., 2011, 2014). After all, real objects differ from pictures, even perfectly matched photos, in many attributes including the availability of binocular depth cues (stereopsis) and motion-based depth cues (motion parallax), consistency between binocular and monocular depth cues, and the potential to act upon the objects. Here we review evidence that adults have a *real-object advantage* (that is, better performance for real objects than pictures) on a variety of tasks, that the difference between real objects and pictures may be reflected in neural processing differences, and that infants also behave differently toward real objects vs. images. Considering this background, the primary goal of the present study was to investigate 7- and 9-month-old infants' visual habituation patterns to real objects and photorealistic pictures of the same objects as well as their preferences for the same items presented in real and picture format following habituation.

Visual Perception of Real Objects and Pictures in Adults

In patients with visual form agnosia, object recognition performance is often enhanced with respect to real objects relative to pictures; a phenomena termed the real-object advantage (Riddoch and Humphreys, 1987; Young and Ellis, 1989; Servos et al., 1993; Humphrey et al., 1994; Chainay and Humphreys, 2001). Additional three-dimensional (3D) object information provided by binocular depth cues (including cues to actual object size based on perceived distance) and richer surface properties such as color, and texture are assumed to contribute to this effect (Servos et al., 1993; Chainay and Humphreys, 2001). More recent research has also shown behavioral advantages for real objects in neurologically intact research participants. Bushong et al. (2010), for example, found that participants in a neuroeconomics study were willing to pay about 50% more when bidding on items (food or trinkets) presented as real objects vs. photographs or text labels. Interestingly, however, they also found that placing a large transparent (Plexiglas) barrier between the participants and stimuli eliminated the effect, suggesting that valuation was not driven by low-level visual features such as binocular disparity, which did not change with the barrier, but rather by the accessibility of the food. Moreover, Snow et al. (2014) demonstrated a differential effect of stimulus format on episodic memory performance. In an initial encoding phase subjects were asked to memorize a total of 44 common household items that were presented either as real objects, color photographs, or black and white line drawings. Following stimulus encoding all subjects were tested for free recall and recognition performance. Results showed that for both episodic memory measures subjects' performance was superior for real objects compared to color photographs and line drawings.

Neural Processing of Real Objects and Pictures in Adults

Recent research has raised the possibility that real objects not only evoke different behavior but may also invoke differences in neural processing. Most notably, Snow et al. (2011) used fMRI to investigate whether real objects and photos evoked similar levels of blood-oxygen-level-dependent (BOLD) activation and whether the response decreased with repetition. Repetition attenuation (also called fMRI adaptation or priming) for images has been commonly observed in object-selective areas; specifically, the presentation of a repeated image (e.g., duck-duck or baseball-baseball) evokes less activation than the presentation of different images (e.g., duck-baseball; Grill-Spector et al., 1999). Such effects are thought to reflect weaker, faster or more finely tuned neural processing for stimuli that have been previously processed, though the exact mechanisms are debated (Grill-Spector et al., 2006). Snow et al. (2014) measured fMRI activation while participants simply viewed pairs of repeated or unrepeated stimuli that were presented either as real objects or visually matched photographs. As expected from past research, robust repetition effects were found for trials containing repetitions of object pictures throughout a wide variety of object-selective brain regions. Surprisingly, however, similar effects were rather weak, if not entirely absent, on trials involving real objects. Notably, the differences in repetition effects were observed even though overall response levels were comparable for objects and photos. These results suggest that the neural processing of real objects differs from photos. One possible interpretation may be that real objects continue to be processed longer than images, perhaps related to the behavioral findings that real objects are more highly valued (Bushong et al., 2010) and memorable (Snow et al., 2014). The fundamental reason for the differences between real objects and images is yet to be determined, but may include differences in stereoscopic depth cues, consistency of monocular and binocular cues to object shape, and the tangibility and potential for actions provided by real objects.

Infants' Visual Perception of Real Objects and Pictures

Behavior and neural processing is enhanced not only in adults but also in infants when they process real objects compared to pictures. Between 5- and 7-months of age infants have developed sufficient visual abilities to discriminate real objects from pictures (Rose, 1977; DeLoache et al., 1979; Slater et al., 1984; Kavšek et al., 2012) but also to perceive their similarities (e.g., Jowkar-Baniani and Schmuckler, 2011). Together with studies that examined infants' manual exploration behavior (DeLoache et al., 1998; Pierroutsakos and DeLoache, 2003; Yonas et al., 2005; Ziemer et al., 2012), these studies provide first indications for a cognitive distinction and thereby for a distinct processing of real objects and pictures.

Infants neural processing also appears to be faster for real objects. In an event-related potentials (ERP) study, Carver et al. (2006) explored the temporal correlates of visual object recognition in 18-month-old infants. One group of infants saw either familiar or unfamiliar real toys, whereas the other group saw pictures of either familiar or unfamiliar toys. Although differences between familiar and unfamiliar toys were seen in late ERP components for both real objects and pictures, differences in early ERP components were found only for the real objects, suggesting that real objects are processed faster than pictures.

Real objects may also be remembered better than pictures in infants, consistent with findings from adults (e.g., Snow et al., 2014). For example, Rose et al. (1983) revealed that 12-month-olds' recognition memory for real objects is less dependent on task specifics such as encoding time. They investigated infants' intramodal and crossmodal transfer from real objects to their pictorial representations. On three trials infants were first visually (intramodal group) or tactilely (crossmodal group) familiarized with real objects, and afterward tested for visual object recognition with the real objects and their pictorial representations. In a first experiment with a 30-s familiarization period, infants in the intramodal group showed substantial object recognition for both real objects and pictures, whereas infants in the crossmodal group revealed significant recognition only for real objects. However, when familiarization time was reduced to 15 s in the intramodal group, infants still recognized real objects but no longer their pictorial representations. Additionally, Ruff et al. (1976) examined 3- and 5-month-old infants' speed in learning to recognize unfamiliar real household objects vs. color photographs of those objects. They created a task that tested infants' visual recognition memory at different points in the experiment and, therefore, verified whether recognition would appear faster for real objects or pictures. Each session involved six familiarization trials with an identical picture or real object interspersed with two paired-comparisons of the familiarization object and a novel object to test for visual object recognition. Their main finding was that only the 5-month-olds exposed to real objects showed solid recognition memory after half of the familiarization trials, indicated by robust novelty preferences from trial three on. Five-month-old infants that were exposed to color photographs, instead, showed no signs of recognizing the photographs throughout the session. Hence, when familiarized to a real object infants seemed to be able to create a mental representation of that object but not when they were familiarized to pictures. The authors concluded that from 5-months on infants learn to recognize real objects faster than pictures of objects. In addition, in the 5-months-olds overall attention to real objects, relative to pictures, declined significantly during familiarization indicated by a larger decrease in fixation time from the first familiarization trial to the last familiarization trial.

However, it is possible that these differences in infants' recognition performance as well as in their familiarization to real objects vs. pictures obtained by Ruff et al. (1976) arose from an insufficient ability to properly perceive pictorial depth cues within the photographs of the complex and unfamiliar household objects they used as stimuli. This is relevant since the perception of depth cues in pictures is a crucial requirement for processing pictures in a similar way as corresponding objects. As a matter of fact, studies that tried to establish the age in which infants start to respond to pictorial depth cues provided divergent results (Kavšek et al., 2012). While preferential reaching methods determine the time of infants' sensitivity to pictorial depth cues between 5 and 7 months of age, research using looking-time methods (habituation-dishabituation and preferential-looking studies) arrive at an age of about 3 to 6 months, largely depending on whether they controlled for an influence of low-level stimulus features on infants' experimental performance. In this case, responsiveness to pictorial depth cues unambiguously emerged only with about 6 months (for a review see Kavšek et al., 2012).

Linking Neural and Infant Habituation Effects

Intriguingly, Turk-Browne et al. (2008) have suggested possible theoretical links between the effects of repetition effects in adult neuroimaging studies and habituation effects in infant behavior studies. Specifically, both approaches typically report decreased responses resulting from stimulus repetition (though increased responses can also occur). These effects can be used to explore representations by examining whether the repetition effects are sensitive to changes to specific attributes of the repeated stimuli. Moreover, they suggest that both approaches may afford increased sensitivity compared to alternative approaches; that is, fMRI repetition effects can reveal effects absent in simple contrasts of activation levels (as observed in the Snow et al., 2011 data) and looking times may reveal earlier sensitivity to certain stimulus features than methods based on measuring actions like reaching or grasping which develop later than vision.

Although there may be some analogies between the techniques, there are also numerous reasons to think that infant habituation and adult fMRI repetition effects are not directly comparable. Most obviously, the participants' ages are very different. In addition, both infant habituation and adult fMRI repetition effects could arise from a wide variety of factors, including memory (Henson, 2003), attention (Moore et al., 2013), processing speed (James et al., 2000), or predictability (Summerfield and de Lange, 2014). fMRI repetition effects can differ between brain areas and some effects are consistent with behavioral signatures of repetition while others are not (e.g., Xu et al., 2007).

Our research question provides an opportunity to conduct a comparison between adult fMRI repetition effects (Snow et al., 2011) and infant habituation results, as shown here using a similar paradigm. Specifically, in both studies we can examine the effects of repeating presentations of real objects or pictures. If Turk-Browne et al. (2008) are correct in surmising an analogy between the approaches, we might expect similar effects in the two types of data; otherwise, we might expect that the specific factors contributing to the two types of effects may lead to inconsistencies in the results.

The Current Study and Hypotheses

Here we examined whether and to which extent infants in their 1st year of life show distinct visual habituation to real objects vs. pictures of the same objects. In multiple trials, we presented 7- and 9-month-old infants with either a real toy or a realistic picture of that toy. In a subsequent test phase, infants' visual recognition memory regarding the objects was evaluated by presenting pairs of the habituation object together with its counterpart in the other format. Note that our test period differs from past work (e.g., Ruff et al., 1976) in comparing two formats – real and picture – of the same object, rather than comparing two different objects in the same format.

Several alternative outcomes are possible and would support different theories. First, different outcomes are possible for the habituation phase. Given the proposed theoretical relationship between neural and infant habituation effects (Turk-Browne et al., 2008), the findings of robust repetition effects for pictures but not real objects in adult fMRI experiments (Snow et al., 2011) would predict robust infant habituation effects for pictures but little or no habituation for real objects (combined with little difference in overall looking times as no differences in overall fMRI activation were observed between real objects and pictures in the fMRI). As one alternative hypothesis, if infants find real objects more engaging because of the richer information they provide (including binocular depth and motion parallax) and their potential for interaction, this would predict longer looking times for real objects. As another alternative hypothesis, if infants are struggling to process pictures due to the relative unfamiliarity of pictures compared to real objects and to the conflicting cues to depth that arise with pictures, this would predict longer looking times for pictures.

Second, different outcomes are possible for the test phase. Assuming infants are able to discriminate a real object from its photo counterpart, they are expected to show preferential looking toward one of the test items. Based on novelty, the prediction would be a preference for the previously unseen stimulus, that is, the real object following adaptation to its photo counterpart and the photo following adaptation to its real counterpart. Based on violation of expectations, the prediction would be a preference for the photo object, which violates the normal relationship between binocular and monocular depth cues, regardless of habituation format. Finally, based on how engaging and valuable the stimulus is, the prediction would be a general preference for the real object, which affords real interaction, regardless of habituation format. DeLoache et al. (2003) argue that even though on a visual level young infants can already discriminate between actual objects and pictures of objects, the full understanding of the representational nature of pictures seems yet to be obtained with 9 months of age (see also Yonas et al., 2005; Ziemer et al., 2012). From this it could be inferred that infants take pictures for objects and would show no clear preference.

For both the habituation phase and the test phase, different theories can yield different, even opposite outcomes. If a clear outcome is obtained, this suggests that one theory yields better predictions that the others, though it is possible effect sizes may be tempered by several factors.

MATERIALS AND METHODS

Ethics Statement

The present study has been realized in accordance to the German Psychological Society (DGPs) Research Ethics Guidelines. For each infant, written consent for participating in the study was obtained from the parents.

Participants

The final sample consisted of 61 healthy and full-term 7-month-old infants at the mean age of 7 months 17 days ($SD = 7$ days; 28 girls and 33 boys) and 59 nine-month-old infants at the mean age of 9 months 19 days ($SD = 8$ days; 28 girls and 31 boys). The data from additional 13 seven-month-old and 8 nine-month-old infants were excluded from the final sample due to fussiness (19), experimenter error (1), or failure of the technical equipment (1). Infants were recruited by obtaining their birth records from local municipal councils and neighboring communities. Participants were predominantly Caucasian infants who lived in Giessen and suburban areas of Giessen.

Stimuli

Stimuli consisted of four different, aged-based toys (mouse, car, frog, and bear) and photographs that were as realistic as possible. The width of the objects ranged from 10.0 to 13.5 cm and the height from 8.5 to 14.0 cm.

Photographs were taken with a good-quality digital camera (Sony DSC-W170 digital camera, 10.1-megapixel resolution). All pictures were taken in the cabin of the experimental setup with the camera placed at the infant's point of view and such that the viewpoint and lighting was the same as that for the real object. Photos were adjusted to real objects pertaining to contrast and brightness with Adobe Photoshop CS6 and printed on photo paper such that the physical size of each matched that of the corresponding real object. For the purpose of stimulus presentation, both real objects and their photographs were fixed to a cardboard which was laminated with black polypropylene and fixed to a wooden box. The final stimulus set consisted of eight stimuli divided into four pairs of real objects and their matched photographs (**Figure 1**).

Apparatus

The experiment was conducted in a white rectangular cabin with an open front to accommodate a caregiver and her child. The child was seated on the caregiver's lap at a distance of approximately 60 cm from the stimuli beyond the infants' reach. From the rear wall of the cabin a 42.5 × 32 cm-sized window was cut out which could be opened and closed via a sliding door made of two black pieces of cardboard. By opening the sliding door a 51 cm × 33 cm × 39 cm enclosed stage appeared which served for presenting the stimuli. For the purpose of placing the stimuli onto the stage its top side was open. The floor of the stage was made of dark chipboard with markers for the correct positioning of the stimuli during the experiment.

During testing, one experimenter measured infants' fixation times while a second experimenter presented the stimuli. Both

FIGURE 1 | Example of a stimulus pair. Stimuli a slightly tilted inward to get a better view on the real object (left hand side) and its matched photograph (right hand side).

experimenters were located behind the setup and hidden from view. The entire session was recorded on a VCR using a low-light video camera which was attached to a peephole in the back of the cabin 5.5 cm above the sliding door. Connected to the camera was a television screen from which infants' gaze behavior could be observed by the first experimenter. Fixation time measurements were taken via a Fujitsu Siemens Lifebook running BABY, a computer software for conducting habituation and preferential looking time experiments (Krist, 2001).

Procedure

All infants were tested in individual sessions. To prevent parents from influencing their babies' fixation times they were asked to keep their eyes closed and to refrain from talking for the duration of the experiment.

To test infants' visual processing and discrimination of real objects vs. pictures, a visual discrimination task was conducted which consisted of a habituation phase and a test phase. In the habituation phase, infants were exposed to one of the four toys either as a real object or picture. The number of infants administered to the four toys in the two different formats (real object and picture) was counterbalanced. To attract infants' attention each trial began with the ringing of a bell from behind the stimuli. After opening the sliding door the habituation stimulus became visible in the middle of the stage. As soon as infants began fixating the stimulus the first experimenter started measuring fixation times by pressing a button. Fixation durations under 1 s were not counted as fixating the stimulus. Trial length was based on infant's fixation of the display. Each trial ended either 2 s after the infant turned her gaze away from the stimulus or after 60 s had passed. The trial continued if the infant returned her attention to the habituation stimulus during the 2-s interval. At the end of a trial the sliding door was closed and the procedure of stimulus presentation described above was repeated. The habituation phase ended when the average fixation time to the stimulus within the last three habituation trials declined to 50% of the average time within the first three habituation trials or when a maximum of 14 habituation trials had been presented. Altogether, infants saw a minimum of 6 and a maximum of 14 habituation trials.

The test phase included three trials with paired-comparisons of the habituation stimulus (real object or picture) together with its counterpart in the other format (novel stimulus). In the first test trial, the novel stimulus was positioned on the left and the habituation stimulus on the right side of infants' gaze direction. After each trial stimuli positions were interchanged. Note that during the habituation phase, only a single item was presented at a time (a given toy either in real or picture format); whereas during the test phase, two items (the same object presented in real and picture format) were presented. An approximately 14-cm distance between the edges of the stimuli ensured reliable measurements of whether infants fixated to the left or to the right test stimulus. Following the general procedure of stimulus presentation from the habituation phase, fixation time measurements started as soon as infants attended to one out of the two stimuli on the stage. Depending on the experimenter's perspective fixations to the right or left test stimulus were indicated by right or left button presses. As in the habituation phase, fixation durations under 1 s were not counted as fixating the stimuli and trial length was again based on infant's fixation of the display. Hence, each trial ended either 2 s after the infant turned her gaze away from the stimuli or after 60 s had passed. The trial continued if the infant returned her attention to one out of the two test stimuli during the 2-s interval.

Trained observers who were naïve to the hypotheses under investigation recorded the time infants spent fixating on the stimuli using videotapes of the sessions. The inter-observer reliabilities of habituation and test phases for both age groups exceeded 0.9.

RESULTS

Experimental results were divided into habituation and test phases.

Habituation Phase

Habituation phase analyses were performed based on Singh et al. (2015) approach, which quantified fixation times for the first two and last two habituation trials. All 120 participants (61 seven-month-olds and 59 nine-month-olds) were included in the analyses of the habituation phase. Fifty-eight of the infants were habituated to real objects (29 seven-month-olds and 29 nine-month-olds) and 62 were habituated to pictures (32 seven-month-olds and 30 nine-month-olds). We conducted a 2 × 2 × 2 repeated-measures ANOVA to examine infants' looking times with habituation trial number (first two habituation trials and last two habituation trials) as a within-participants variable and age group (7-month-olds or 9-month-olds) and habituation stimulus format (real object or picture) as between-participants variables. A preliminary ANOVA with a fourth factor of object identity (mouse, car, frog or bear) revealed no significant main effect of object identity nor interactions with object identity (all Fs < 1.38, all ps > 0.25); thus, we collapsed across this factor to simplify the analyses.

Most interestingly, as shown in **Figure 2**, infants spent significantly more time looking at stimuli in the first two trials compared to the last two trials and this effect was significantly more pronounced for real objects than pictures. That is, infants spent more time looking at real objects than pictures initially; however, over the course of habituation, the looking times for real objects dropped at a faster rate than for pictures until they were similar between the two formats.

Statistically, this pattern is indicated by the 3-way ANOVA, which revealed both a main effect of habituation trial number, $F(1,116) = 72.15$, $p < 0.001$, $\eta_p^2 = 0.383$, and an interaction between habituation trial number and habituation stimulus format, $F(1,116) = 6.52$, $p < 0.05$, $\eta_p^2 = 0.053$. *Post hoc t*-tests revealed significant decrements in looking times with habituation for both stimulus formats, $t(57)_{real\ objects} = 6.36$, $p < 0.001$, $d = 1.09$, and, $t(61)_{pictures} = 5.37$, $p < 0.001$, $d = 0.84$, and significantly longer looking times for real objects on the first two trials, $t(118) = 2.24$, $p < 0.05$, $d = 0.41$, but not the last two trials, $t(118) = -0.65$, $p > 0.05$, $d = -0.12$. In addition,

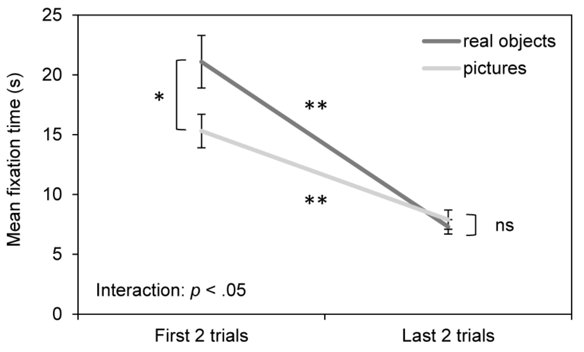

FIGURE 2 | Results of the habituation phase. Mean fixation time (s) for real objects and pictures during the first two habituation trials and the last two habituation trials. Error bars indicate the standard error of the mean. *$p < 0.05$, **$p < 0.001$.

the ANOVA revealed a main effect of age, such that 9-month-old infants fixated longer on the stimuli than 7-month-old infants; however, there was only a trend toward an interaction between age group and habituation trial number, $F(1,116) = 3.53$, $p = 0.063$, $\eta_p^2 = 0.030$ and no significant three-way interaction of age group × habituation trial number × habituation stimulus format, $F(1,116) = 2.44$, $p > 0.05$, $\eta_p^2 = 0.021$. In addition, there was a trend toward a main effect of format but this must be considered in light of its interaction with habituation trial number.

We also analyzed infants' accumulated looking times (that is the sum of looking times across all trials in the habituation phase) via a 2 × 2 ANOVA with age group and habituation stimulus format as between-participants variables. Again, a preliminary ANOVA with object identity as a third factor yielded no significant main effect of object identity nor interactions with object identity (all Fs < 1.62, all ps > 0.19); thus, we collapsed across this factor to simplify the analysis.

Concerning accumulated looking times, there was a main effect of age group, $F(1,116) = 4.24$, $p < 0.05$, $\eta_p^2 = 0.035$, but more importantly no main effect of habituation stimulus format nor an interaction between the two factors (all Fs < 0.71, all ps > 0.40). Overall, 9-month-old infants fixated longer on the stimuli than 7-month-old infants, but accumulated looking times did not differ between real objects and pictures.

Test Phase

Prior to test phase analyses, 18 seven-month-old and 15 nine-month-old infants were excluded because they failed to reach the habituation criterion within the 14-trial maximum of the habituation phase. The data of additional 10 seven-month-olds and 4 nine-month-olds were excluded because they failed at least once on fixating to one out of the two test stimuli during the three test trials. Thus, test results are based on the data of 73 infants. Forty-one of the infants were habituated to real objects (18 seven-month-olds and 23 nine-month-olds) and thirty-two of the infants were habituated to pictures (15 seven-month-olds and 17 nine-month-olds). In order to test for infants' visual preferences during the test phase following habituation, a preference score on the percentage of time each infant spent fixating to the novel object (real object or picture) across all three test trials was calculated by dividing fixation time to the novel object by overall fixation time multiplied by 100.

We conducted a 2 × 2 ANOVA examining the effects of the two age groups (7-month-olds or 9-month-olds) and habituation stimulus format (real object or picture) on the preference score for novel objects. A preliminary ANOVA with a third factor of object identity (mouse, car, frog, or bear) revealed no significant main effect of object identity nor interactions with object identity (all Fs < 2.04, all ps > 0.11); thus, we collapsed across this factor for the following analyses.

The 2 × 2 ANOVA on the preference score for novel objects with age group and habituation stimulus format as between-participants variables revealed a significant main effect of habituation stimulus format, $F(1,69) = 17.38$, $p < 0.001$, $\eta_p^2 = 0.201$, but no additional main effect of age group or interaction (all Fs < 0.85, all ps > 0.36). Infants who were habituated to real objects showed a familiarity preference ($M = 46.1\%$, $SE = 1.3$), indicating that they kept preferring to look at real objects during the test. For infants who were habituated to pictures of objects, our analyses revealed a preference for novel objects ($M = 54.8\%$, $SE = 1.6$) and therefore, again, for real objects (**Figure 3**). In order to contrast the preference scores for novel objects separately for the two habituation stimulus formats against chance level, *post hoc* single t-tests were performed (Bonferroni corrected). The t-tests confirmed the preference for real objects to be significantly different from chance level for infants who were habituated to real objects, $t(40) = -2.93$, $p < 0.01$, $d = 0.46$, as well as for infants who were habituated to pictures of those objects, $t(31) = 2.95$, $p < 0.01$, $d = 0.52$.

DISCUSSION

The principal motivation of the present study was to examine 7- and 9-month-old infants' visual habituation to real objects and pictures of those objects to provide new insight into the basic visual processing of objects varying in format. Our results revealed three key findings: (1) infants spent more time looking at real objects than pictures during the initial habituation trials; (2) they habituated to real objects faster than to pictures such that, at the end of habituation, they looked equally at the stimuli regardless of format; and (3) following habituation, during test trials where a habituated stimulus was paired with the same stimulus in the other format, infants preferred looking at the real object, regardless of whether they had become habituated to the real object or picture version. These effects did not differ significantly between the two age groups. Moreover, differences in the habituation and the test phase were not determined by differences in accumulated looking times during habituation, which was the same for real objects and pictures, although the older infants did spend more time fixating on the stimuli overall (including during the initial presentations). At first sight, these more pronounced fixation times in the older infants may

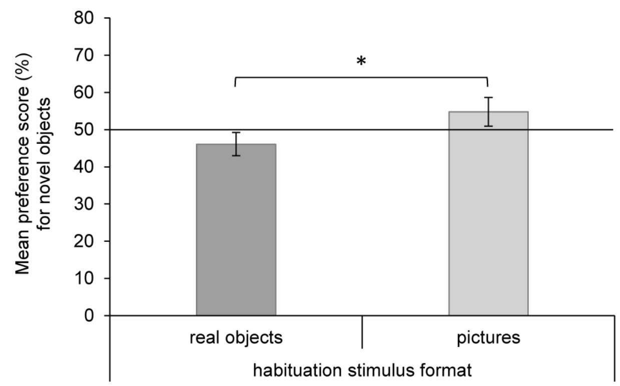

FIGURE 3 | Results of the test phase. Mean preference score (%) for novel objects (real object or picture) in the two habituation stimulus format groups. Error bars for the preference scores are based on the 97.5% confidence intervals, which indicate whether or not the average preference (Bonferroni corrected) was significantly greater or lower than 50%. $^*p < 0.001$.

seem unusual because traditional habituation research often finds shorter fixation durations with age (for an overview see Colombo and Mitchell, 2009); however, the relationship between age and fixation duration in infant attention may not be straightforward and may depend on the type of stimuli employed. For complex and interactive stimuli, fixation duration seems to increase with age (Courage et al., 2006; Reynolds, 2015). Because we presented highly relevant age-based toys within a live setup, older infants may have been particularly engaged by the stimuli, leading to greater fixation times overall (including at the beginning of habituation when infants' baseline attention was assessed).

Our habituation data reveal that children demonstrate a real-object advantage as previously demonstrated in adults (Riddoch and Humphreys, 1987; Servos et al., 1993; Humphrey et al., 1994; Chainay and Humphreys, 2001; Bushong et al., 2010; Snow et al., 2014) and children from infancy on (Ruff et al., 1976; Rose et al., 1983). Moreover, they are in agreement with electroencephalography results that suggested enhanced processing of real objects compared to pictures in infants 18-months of age (Carver et al., 2006), and suggest that the real-object advantage extends to infants as young as 7-months-old.

A second aim of the present study was to examine infants' ability to discriminate real objects from pictures of objects. The present results showed that 7- and 9-month-old infants were able to discriminate real objects from pictures and that both age groups preferred to look at real objects, independent of whether they were habituated to real objects or pictures. These results are consistent with a small number of studies that have reported preferences for real objects over pictures in the absence of habituation. DeLoache et al. (1979) found that 5-month-old infants spontaneously preferred to look at real dolls than color photographs of the same dolls. In contrast, Slater et al. (1984) found a spontaneous preference for real objects in one experiment and a preference for pictures of objects in another one. However, Fantz and Nevis (1967) point to a shift with age in preference from pictures to real objects in infants which might be due to an increasing awareness of the affordances of real objects.

What is particularly striking about the present results is that the real-object preference persists even after infants have fully habituated to real objects. This aspect of the findings is not consistent with a preference for novel objects nor with a preference for items that violate expectations. Rather, it shows that real objects are more attention-grabbing even when they are familiar. This could be due to the richness of visual information provided by real objects but not pictures, including stereo depth and motion parallax, or to the fact that real objects are more compelling and valuable because they are tangible and afford actions. Certainly, the latter goes well together with a nativist claim of innate predilections that dispose the newborn infant to focus attention on stimuli that will later on have adaptive significance (Fantz, 1961), such as preferences for human speech-sounds (e.g., Vouloumanos and Werker, 2007; Shultz and Vouloumanos, 2010) or human faces (Mondloch et al., 1999).

Note that the real stimuli we employed were quite flat and shallow, so if stereo depth is a key factor, then the effects may be expected to be even larger with stimuli that have more depth structure. Future studies could tease apart the contributions of these factors by having infants view the stimuli monocularly to eliminate stereo vision, restricting head movements or employing a virtual display that keeps the view constant with head movements to restrict motion parallax, and examining groups with different degrees of hands-on vs. visual experience with the real objects.

Our results call into question a straightforward relationship between infant habituation and fMRI repetition effects, as has been proposed by Turk-Browne et al. (2008). Specifically, fMRI studies found repetition effects for pictures but not real objects (Snow et al., 2011), which would lead to a prediction that infants would also habituate to pictures but not real objects. In fact, we found the converse – greater habituation to real objects than to pictures. Despite the absence of a direct mapping of results between the two techniques, the fMRI and infant habituation studies may nevertheless reveal commonalities of a real-object advantage across the age groups and methods. The similarity lies in the finding that for "both babies and brains," real objects are more engaging both perceptually and neurally and evoke longer processing. In fMRI, this is reflected by prolonged processing of real objects (that is, weak or absent repetition effects); whereas, in infant behavior, it is reflected by prolonged looking times. Thus, while there is merit to the proposal that infant habituation and fMRI adaptation may tap into related mechanisms (Turk-Browne et al., 2008), there also appear to be important differences in cognitive processing between infants and adults and between what is measured by behavior and fMRI. Most notably, fMRI repetition effects may result from a variety of neural mechanisms (Grill-Spector et al., 2006) and be influenced by memory (Henson, 2003), attention (Moore et al., 2013), or expectations (Summerfield and de Lange, 2014). Moreover, fMRI repetition effects are not always consistent with behavioral differences (e.g., Xu et al., 2007).

In summary, our findings indicate that 7- and 9-month-old infants show a robust preference for looking at real objects instead of their pictorial representations but upon the initial encounter and following prolonged viewing.

AUTHOR CONTRIBUTIONS

JC and GS conceptualized and designed the work and were involved in interpreting the data. They gave their final approval of the work to be published as well as their agreement to be accountable for all aspects of the work. JC was involved in drafting the work and in revising it critically. GS was involved in revising the work critically. TG was responsible for the acquisition, analysis, and interpretation of the data and drafting the work. She gave her final approval of the work to be published and agrees to be accountable for all aspects of the work.

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Manual exploration of objects is related to 7-month-old infants' visual preference for real objects

Theresa M. Gerhard[1]*, Jody C. Culham[2], Gudrun Schwarzer[1]

[1]Department of Developmental Psychology, Justus-Liebig-University Giessen, Giessen, Germany

[2]Department of Psychology and Brain and Mind Institute, University of Western Ontario, London, Canada

***Corresponding author:**

Theresa M. Gerhard,

Department of Developmental Psychology

Otto-Behaghel-Str. 10 F

Justus-Liebig-University Giessen

35394 Giessen, Germany

E-Mail: theresa.gerhard@psychol.uni-giessen.de

Abstract

The present study examined whether infants' visual preferences for real objects and pictures is related to their bimanual object exploration skills. Fifty-nine 7-month-old infants were tested in a preferential looking task with a real object and its pictorial counterpart. All of the infants also participated in a manual object exploration task, in which they were allowed to freely explore five toy blocks. Infants with a higher level in fingerings, that is, going with the tip of their fingers over the surfaces and edges of objects, showed a preference for real objects during the preferential looking task. In comparison, infants with a low level in fingerings showed no preferences. Our findings suggest that experience with specific exploratory actions might improve infants' understanding of the differences in format regarding real objects and pictures.

Keywords: Infancy, Motor development, Perception

Introduction

From early in life, infants encounter real, physical objects in their environment as well as pictorial representations of those objects. Consequently, within the first year they have to deal with objects in different formats on a regular basis. Between 5- and 7-months of age infants have developed sufficient perceptual abilities to visually discriminate real objects from pictures (DeLoache, Strauss, & Maynard, 1979; Kavšek, Yonas, & Granrud, 2012; Rose, 1977; Slater, Rose, & Morison, 1984) but also to perceive their similarities (Dirks & Gibson, 1977; Rose, 1977; Slater et al., 1984). More interestingly, they even show a visual preference for real objects over pictures when presented with both object formats at the same time (DeLoache et al., 1979; Gerhard, Culham, & Schwarzer, 2016), indicating a distinct visual processing of real objects and pictures.

In developmental psychology there is broad agreement that biological maturation closely interacts with experiential factors in perceptual development. However, there is more research needed to link age specific types of experience to certain perceptual capabilities (Schwarzer, 2014). It is still unclear, for example, which experiential factors may facilitate such a preference for real objects over their picture versions. Previous research suggests that experiences with objects gained during motor activity such as bimanual object exploration are crucial for infants' visual perception and their understanding of object properties (see Libertus & Hauf, 2017; Schwarzer, 2014; Soska, Adolph, & Johnson, 2010). The present study, therefore, seeks to investigate whether sophisticated manual object exploration skills (i.e., transfers, fingerings, and rotations) are related to infants' visual preference for real objects.

Preference for real objects over pictures during infancy

There is good evidence that during infancy real objects become more attention-grabbing than pictures of objects. For example, in a control experiment DeLoache, Pierroutsakos, Uttal, Rosengren, and Gottlieb (1998) examined 9-month-old infants' discrimination of real objects and their pictures with a preferential reaching task. Infants were presented with picture books containing picture-object pairs of eight small toys and color photos of those toys. Results showed that 86% of the infants' first reaches were directed toward the real objects, indicating both infants' discrimination abilities of real objects and the corresponding pictures and their preference for real objects over pictures.

Further evidence pointing to a preference for real objects comes from looking time studies. Slater et al. (1984) conducted a series of experiments with newborns to give new insight into infants' detection of similarities and differences between simple and complex objects and their corresponding pictures. In some of their experiments a visual preference paradigm was employed to test whether the newborns are able to spontaneously discriminate between the real and picture versions of the stimuli. The results of the experiments were found to be ambiguous. Infants showed a preference for real objects in one series of experiments using the more complex stimuli and a preference for pictures in another experiment with the simpler stimuli.

A clearer indication of a visual preference for real objects over pictures was given by DeLoache et al. (1979). In two experiments they investigated 5-month-old infants' ability to visually transfer information from real objects to pictures of objects (two dolls and pictures of those dolls), and within pictorial stimuli. In a side experiment, infants were preference tested with the real dolls and their color pictures to test for visual discrimination ability. Results revealed that the 5-month-olds spontaneously preferred to look at real dolls during the visual preference procedure.

In line with DeLoache and her group (1979), Gerhard et al. (2016) found a visual preference for real objects over their pictures in 7- and 9-month-old infants despite previous habituation. Infants in this study were first habituated to either a real toy or a picture of a toy and afterwards preference tested with the habituation stimulus together with its counterpart in the other format (real toy or picture). During the paired-comparison infants of both ages showed a preference for real toys, regardless of whether they had become habituated to the real toy or picture version of that toy. Interestingly, in the beginning of habituation where either a real object or a picture was presented, infants payed more attention to the real objects than to the pictures, indicated by longer looking times. The authors concluded that the richness of visual information provided by real objects but not pictures (including stereo depth and motion parallax), and the fact that real objects are more valuable because they are tangible and afford actions could be accounted for the infants behavior.

Altogether, the studies reported stress the notion that real objects are more attention-grabbing than pictures of objects even when they are familiar.

Manual object exploration in the processing of object properties during infancy

In developmental research there has been a long history of linking infants' progress in perceptual abilities to their motor experiences. Piaget (1952) argued that sensorimotor experiences or actions facilitate infants' understanding of object properties because they enable access to certain object information that are unlikely to be detectable by vision alone, such as texture, hardness, and shape (see also Lederman & Klatzky, 1987, 1993). Other researchers have further elaborated that increasing activity with objects fine-tune infants' perceptual systems to the association between characteristics of objects and the actions they afford (Adolph, Eppler, & Gibson, 1993; Bushnell & Boudreau, 1993; E. J. Gibson, 1988). Indeed, recent neuro-electrophysiological evidence suggests that visual-manual object exploration modulates frontal theta-band activity in the infant brain that is predictive for implicit learning of object properties and subsequent object recognition performance (Begus, Southgate, & Gliga, 2015).

Behavioral studies focusing on infants' object exploratory skills have provided additional evidence for an association between manual object exploration and object processing abilities. Newborns were found to cross-modally transfer object information from touch to vision, indicating an early link between manual action and the visual processing of objects (Sann & Streri, 2007; Streri & Gentaz, 2004). Six-month-olds' ability to integrate different object dimensions such as size, texture, and shape into visual perception of whole objects was bound to previous acquisition of visual-haptic experience with the objects (Jovanovic, Duemmler, & Schwarzer, 2008). Additionally, infants' visual and oral exploration while holding objects is positively related to the understanding of object segregation (Needham, 2000), and to responsiveness regarding changes in object appearance (Perone, Madole, Ross-Sheehy, Carey, & Oakes, 2008). Soska et al. (2010) studied the link between developmental changes in 4.5- to 7.5-month-old infants' motor skills and their ability of three-dimensional object completion (ability to perceive the unseen backs of objects). The authors focused on two types of motor skills self-sitting ability and, importantly, coordinated visual-manual object exploration. Rotating objects, fingering objects, and transferring them between the hands were thought to be especially useful in infants' learning about the three-dimensional nature of objects because they provide active experience with multiple object views, as well as visual-tactile information about object form and contour. Results showed that these sophisticated manual exploration skills were indeed a powerful predictor of performance in the three-dimensional object completion task.

The research group of Amy Needham and others (Libertus, Joh, & Needham, 2016; Libertus & Needham, 2010; Wiesen, Watkins, & Needham, 2016) was able to provide evidence for a *causal* relationship between infants' self-produced object exploration experience and object processing abilities within the framework of a training study starting with pre-reaching infants at 3 months of age. Not only did they show that infants who had participated in a 2-weeks manual exploration training with sticky mittens advanced in their manual but also in their visual exploration of objects (Libertus & Needham, 2010). Notably, two months after the initial training, infants who had received the manual exploration training still showed more sophisticated object exploration than infants who did not receive such an active training (Wiesen et al., 2016). The effect persisted even until 12 months after the training and the actively trained infants were also more advanced in focusing their visual attention while exploring an object (Libertus et al., 2016). To summarize, it can be noted that the development of bimanual object exploration skills has substantial impact on infants' perception of object properties and the possible actions they afford.

The current study

The present study examined the relationship between 7-month-old infants' bimanual object exploration skills and their visual preference for real objects and pictures of those objects.

In order to test for infants' visual preferences regarding real objects and their pictorial counterparts we employed a preferential looking task in which the infants were presented with a real toy next to its picture version. We chose to study 7-month-old infants because with 7 months of age infants have developed sufficient abilities to properly perceive pictorial depth cues (Kavšek et al., 2012), a crucial requirement for visually processing pictures in a similar way as corresponding objects.

According to Soska et al. (2010), we also tested for infants' coordinated visual-manual object exploration skills with focusing on manual actions such as fingering objects, transferring objects between the hands, and rotating them. These more sophisticated exploratory actions are supposed to promote infants' learning about the three-dimensional form of objects. With 7 months infants have also learned to switch among such exploratory actions more frequently (Lobo, Kokkoni, de Campos, & Galloway, 2014), providing them with sufficient information about the crucial differences regarding form and tangibility of real objects compared to pictures.

Therefore, we hypothesized that this specific manual experience with objects may lead infants to focus their visual attention more on real objects than their pictures when presented with both object formats simultaneously. However, we did not have clear predictions about whether all of the three exploratory actions matter or whether there are unique contributions. We hypothesized, though, that infants who are more advanced in their manual object exploration skills show a stronger preference for real objects in the preferential looking task than the less advanced infants.

Material and Methods

Ethics Statement

The present study has been realized in accordance to the German Psychological Society (DGPs) Research Ethics Guidelines. For each infant, written consent for participating in the study was obtained from the parents.

Participants

The final sample consisted of 59 healthy and full-term seven-month-old infants at the mean age of 7 months 18 days (*SD* = 7 days; 30 girls and 29 boys). The data from additional 8 infants were excluded from the final sample due to fussiness (1), experimenter error (2), failure of fixating on both stimuli in at least one of the three test trials during the visual paired-comparison task (4), or a side bias of looking to the same side more than 80% of the time in each of the three test trials (1). Infants were recruited by obtaining their birth records from local municipal councils and neighboring communities. Participants were predominantly Caucasian infants who lived in BLINDED FOR REVIEW and suburban areas of BLINDED FOR REVIEW.

Stimuli

Preferential looking task

The stimuli used for the warm-up trial consisted of an identical pair of a purple, two-dimensional blossom with an attached three-dimensional, green and yellow ladybug. The width and the height of the blossom was 19 cm. The ladybug had a width of 3.8 cm and a height of 4 cm. Stimuli were fixed to a cardboard which was laminated with black polypropylene and fixed to a wooden box.

Stimuli for the test trials consisted of four different, aged-based toys (mouse, car, frog, and bear) and photographs that were as realistic as possible. The width of the objects ranged from 10.0-13.5 cm and the height from 8.5-14.0 cm.

Photographs were taken with a good-quality digital camera (Sony DSC-W170 digital camera, 10.1-megapixel resolution). All pictures were taken in the cabin of the experimental setup with the camera placed at the infant's point of view and such that the viewpoint and lighting was the same as that for the real object. Photos were adjusted to real objects pertaining to contrast and brightness with Adobe Photoshop CS6 and printed on photo paper such that the physical size of each matched that of the corresponding real object. For the purpose of stimulus presentation, both real objects and their photographs were likewise fixed to a cardboard which was laminated with black polypropylene and fixed to a wooden box. The final stimulus set consisted of eight stimuli divided into four pairs of real objects and their matched photographs (Figure 1).

Please insert Figure 1 about here

Manual object exploration task

The stimuli for the manual object exploration task consisted of five toy blocks, each between 6 cm and 10 cm wide (see Figure 2). They fit easily into infants' hands and were readily graspable. All objects were made of soft cloth or wood and had colorful patterns on the front and back.

Please insert Figure 2 about here

Apparatus and Procedure

All infants were tested in individual sessions. The order of the preferential looking task and the manual object exploration task was counterbalanced across infants.

Preferential looking task

The experiment was conducted in a white rectangular cabin with an open front to accommodate a caregiver and her child. The child was seated on the caregiver's lap at a distance of approximately 40 cm from the stimuli beyond the infants' reach. From the rear wall of the cabin a 42.5 x 32 cm-sized window was cut out which could be opened and closed via a sliding door made of two black pieces of cardboard. By opening the sliding door a 51 cm x 33 cm x 39 cm enclosed stage appeared which served for presenting the stimuli. For the purpose of placing the stimuli onto the stage its top side was open. The floor of the stage was made of dark chipboard with markers for the correct positioning of the stimuli during the experiment. To optimize lighting conditions on stage two light bulbs were placed at the backside of the cabin right above the window.

During testing, one experimenter controlled for trial length while a second experimenter presented the stimuli. Both experimenters were located behind the setup and hidden from view. The entire session was recorded on a VCR using a low-light video camera which was attached to a peephole in the back of the cabin 5.5 cm above the sliding door. Connected to the camera was a television screen to monitor infants' behavior during the task. Trial length was controlled via a Fujitsu Siemens Lifebook running BABY, a computer software for conducting habituation and preferential looking time experiments (Krist, 2001).

To prevent parents from influencing their babies' fixation times they were asked to keep their eyes closed and to refrain from talking for the duration of the experiment.

The preferential looking task consisted of a warm-up trial to accustom infants with trial procedure, and three test trials. In the warm-up trial, infants were exposed to the respective stimulus pair (blossom with ladybug) standing next to each other at a distance of approximately 14 cm between the edges of the stimuli. To attract infants' attention the trial began with the ringing of a bell from behind the stimuli. After opening the sliding door the two stimuli became visible. As soon as the sliding door had been fully opened up, the experimenter controlling for trial length started the warm-up trial by pressing a button. Each trial had a duration of 15 s. At the end of the trial the sliding door was closed again. The test trials followed the same structure as the warm-up trial but differed in the object pair used.

Infants were presented with the real object together with its picture of one of the four toys (mouse, car, frog, or bear). The number of infants administered to the four toy pairs was counterbalanced. In the first test trial, half of the infants started with the real object being presented to the right and the picture being presented to the left of their gaze direction, while this order was reversed for the other half of infants. After each trial stimulus positions were interchanged.

Trained observers who were naïve to the hypotheses under investigation recorded the time infants spent fixating on the test stimuli frame by frame using the video tool Virtualdub and videotapes of the sessions. Another observer scored 50% of the data to verify the reliability of the codes. Inter-observer reliabilities exceeded 0.9 (Pearson's *r*).

Manual object exploration task

The manual object exploration task was conducted at a table where infants were seated on their caregiver's lap. An experimenter offered the infants five objects one at a time, for one trial each, in a counterbalanced order across the sample. Each trial started with the experimenter presenting the object at midline. The trial lasted from the moment when the infants grasped the object until they had accumulated 40 s of spontaneous manual exploration. If infants dropped the object and did not recover it within 5 s, the experimenter offered the object again. After 40 s of accumulated manual exploration, the experimenter removed the object from infant's hand and offered the next object.

The entire session was recorded on a VCR by a camera placed diagonally to the left of the infants. A coder scored the object exploration data using the video tool Virtualdub to determine the frequencies of the infants' actions. According to Soska et al. (2010), we focused our analyses on fingerings, rotations, and transfers preformed while infants looked at the objects for at least 0.5 s. A fingering was scored when infants moved their fingers over the surfaces and edges of the object; a rotation was scored when the rotation of an object subtended at least 90°; a transfer was scored when the infants transferred an object between hands with less than 5 s of both hands holding it. A second coder scored 50% of the data to verify the reliability of the codes. Inter-coder reliability for fingerings, rotations, and transfers exceeded 0.88 (Pearson's *r*).

Results

In order to test for infants' visual preferences in the preferential looking task, we calculated average preference scores on the percentage of time infants spent fixating to real objects and to pictures (inverse of the preference score for real objects) in the three test trials.

To assess the effects of manual object exploration skills on the preference scores for the two object formats (real objects and pictures), we calculated the median of transfers, fingerings, and rotations and divided subjects' into two categories of low explorative infants (category 1 ≤ median of actions), and highly explorative infants (category 2 > median of actions) for each of the three object exploratory actions. The median of transfers was 3.0 (category 1 = 35 infants, category 2 = 24 infants), the median of fingerings was 4.0 (category 1 = 30, category 2 = 29), and the median of rotations was 8.0 (category 1 = 30, category 2 = 29).

We conducted two repeated-measures ANOVAs to analyze our data. First, in a preliminary ANOVA, we examined the effects of object identity (mouse, car, frog or bear), order of stimulus position (real object starting to the right vs. real object starting to the left), and order of the manual object exploration task (prior to visual-paired comparison task vs. after visual-paired comparison task) as between-subjects variables on the preference scores for the two objects formats (real objects and pictures) as the within-subjects variable. The ANOVA revealed no reliable main effects or interactions (all Fs < 1.51, all ps $> .22$); thus, we collapsed across these factors to simplify the analyses.

With a second repeated-measures ANOVA the effects of transfers (low explorative vs. highly explorative), fingerings (low explorative vs. highly explorative), and rotations (low explorative vs. highly explorative) as between-subjects variables on the preference scores for real objects and for pictures as the within-subjects variable were explored. The analysis revealed a main effect of object format, suggesting that independent of their manual object exploration skills infants preferred to look at real objects (M = 53.4%, SE = 1.1) when presented with both object formats simultaneously, $F(1,51) = 6.62$, $p < .05$, partial $\eta^2 = .115$. A *post-hoc* single *t*-test confirmed this overall preference for real objects to be significantly different from chance level, $t(58) = 2.86$, $p < .01$, $d = 0.37$. Most interestingly, whereas the same analysis showed no effects of transfers, $F(1,51) = 1.91$, $p > .05$, partial $\eta^2 = .036$, rotations, $F(1,51) = 0.33$, $p > .05$, partial $\eta^2 = .006$, nor any interactions of the three exploratory actions (all Fs < 0.46, all ps > .50), it revealed a significant interaction between object format and fingerings, $F(1,51) = 7.45$, $p < .01$, partial $\eta^2 = .127$. This interaction indicates that low explorative and highly explorative infants in this particular skill differed with regard to their visual preference for real objects in the preferential looking task. Infants with a low score in fingering the objects during the manual object exploration task showed neither a visual preference for real objects nor for pictures (M = 49.9, SE = 1.7), whereas infants with a high score in fingerings preferred to look at the real objects (M = 57.0, SE = 1.4). In order to contrast the preference scores for real objects separately for the two exploration groups against chance level, *post-hoc* single *t*-tests were performed (Bonferroni corrected). The *t*-tests confirmed that low exploratory infants showed no preference for real objects, $t(29) = -0.05$, $p > .05$, $d = -0.01$. In comparison, highly explorative infants significantly preferred to look at real objects when presented with both stimuli simultaneously, $t(28) = 5.04$, $p < .001$, $d = 0.93$ (Figure 3).

Please insert Figure 3 about here

Discussion

The principal motivation of the present study was to examine whether 7-month-old infants' visual preference for real objects compared to pictures of those objects is related to their bimanual object exploration skills. Our results revealed a general preference for real objects that was associated with infants' level of fingerings during the manual object exploration task. Infants with a high level in fingerings showed a clear preference for looking at real objects, whereas infants with a low level in fingerings showed no preference for either object format.

Visual preferences for real objects over pictures in infants independent of motor abilities were found before (DeLoache et al., 1979; Gerhard et al., 2016; Slater et al., 1984). Notably, Gerhard et al. (2016) demonstrated similar visual preferences for real objects within the same age group. This can be taken as evidence that during the first year of life real objects become more attention-grabbing than pictures. The present study replicates these findings and extents them in such a way that experiences with certain motor behaviors seem to advance infants' perception of object properties such as format.

That real objects become more attention-grabbing than pictures of objects early in life may not be so surprising considering the several attributes in which they differ from each other. First, when viewed with two eyes real objects compared to pictures possess additional binocular and motion-based depth cues (stereopsis, motion parallax) to infer three-dimensional object shape. Second, real objects present the visual system with consistent binocular and monocular depth cues whereas pictures present the visual system with inconsistent binocular and monocular depth cues; while monocular cues such as specular highlights, surface texture, and linear perspective indicate that the stimulus has depth, binocular cues indicate that the stimulus is flat (Vishwanath & Kowler, 2004). Furthermore, real objects are tangible and afford actions in a way that pictures do not. There is ample evidence from studies with adults and infants that these differences between real objects and pictures regarding binocular and monocular depth cues elicit distinct neural (Carver, Meltzoff, & Dawson, 2006; Snow et al., 2011), and behavioral responses (e.g., Bushong, King, Camerer, & Rangel, 2010; Gerhard et al., 2016; Snow, Skiba, Coleman, & Berryhill, 2014), even though their respective contributions cannot be drawn directly from the data of these studies. Likewise, the experimental design of the present study does not allow for conclusions on the exact role of these cues in 7-month-old infants' visual preference for real objects. Teasing apart their contributions needs, therefore, to be addressed in future work by having infants view the stimuli monocularly to eliminate stereo vision, restricting head movements or employing a virtual display that keeps the view constant with head movements to restrict motion parallax, and examining groups with different degrees of hands-on vs. visual experience with the real objects (Gerhard et al., 2016).

DeLoache et al. (1998) propose that through experiences infants learn a great deal about the differences between pictures and the real entities they represent, including that pictures are not real objects. Motor activity is the means by which we acquire these experiences and has been considered as a crucial force in perceptual development for a long time. Piaget (1952) argued that sensorimotor experiences or actions mark the basis for infants' developing object processing skills and their understanding of the world. Likewise, theories of embodied cognition assume tight links between the body and cognitive abilities (Needham & Libertus, 2011; Smith & Gasser, 2005; Thelen, 2000), and ecological approaches emphasize the role of sensorimotor actions as a means to acquire new information (E. J. Gibson, 1988; J. J. Gibson, 1979). In particular, Soska et al. (2010) provided evidence that same manual exploratory skills as investigated in the current study – that is, transfers, fingerings, and rotations – facilitate infants‘ ability to perceive the three-dimensional form of objects. The present study contributes to these approaches by demonstrating that infants' preference for real objects is related to their sensorimotor experiences, i.e., the way they manually explore objects.

One might ask, however, why in our study it was only fingerings accounting for infants' preference for real objects and not transfers, or rotations. In adults, apprehension of certain object properties are linked to specific exploratory procedures (Lederman & Klatzky, 1987, 1993). In infants, especially during the first year of life rapid development in postural, and manual control leads to a better match between their increasing repertoire of exploratory behaviors and object properties or affordances (Lobo et al., 2014). With regard to capturing differences in volume and shape, manual actions such as enclosing objects with the hands and, importantly, following contours and edges are supposed to be particularly useful. Even though fingerings may not represent the full capacity of what Lederman and Klatzky (1987) define as contour following in adults, it can be considered as an antecedent skill for this kind of exploratory procedure that gives rise to knowledge about structure-related object properties. In addition, Rochat (1989) stresses fingerings as a special means for a fine haptic scanning of objects because it involves contacting objects with the most sensitive parts of the hand. In summary, out of the three exploratory actions of interest (transfers, fingerings, and rotations) fingerings may serve to be particularly effective in gathering information regarding three-dimensional form differences between real objects and pictures.

However, a limitation of the present study is that we cannot provide information about the developmental course of relations between manual object exploration skills (i.e., fingerings) and visual preferences for real objects over pictures because the factor of age was held constant in our design. Additionally, regarding our three manual actions of interest infants were classified in highly and low explorative infants. This leaves open the possibility that another factor contributes to the relationship between fingerings and preferential looking at real objects. Providing infants that are not yet able to systematically explore object properties through fingerings with corresponding experiences could be a suitable way to overcome this limitation. One has to bear in mind though that this would likely involve studying infants between 5-6 months of age (Eppler, 1995), a point in time that is also critical for the emergence of infants' sensitivity to pictorial depth cues between 5 and 7 months (Kavšek et al., 2012). A true influence of a training in manual object exploration behaviors on preferential looking to real objects over pictures can only be accepted when infants are able to perceive pictures of objects in a similar way than corresponding real objects, something pictorial depth perception is crucial for.

In conclusion, our findings show for the first time that 7-month-old infants' experiences with exploring objects via fingerings are positively related to their visual preference for real objects.

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Figure Captions

Figure 1:

Example of a stimulus pair. Stimuli a slightly tilted inwards to get a better view on the real object (left hand side) and its matched photograph (right hand side).

Figure 2:

Toy objects used in the manual object exploration task.

Figure 3:

Results of the preferential looking task. Mean preference score (%) for real objects in infants with a high score in fingerings and infants with a low score in fingerings. Error bars for the preference scores are based on the 97.5% confidence intervals, which indicate whether or not the average preference (Bonferroni corrected) was significantly greater or lower than 50%. Note: *$p < .01$; **$p < .001$; ns, nonsignificant.

Figure 1

Figure 2

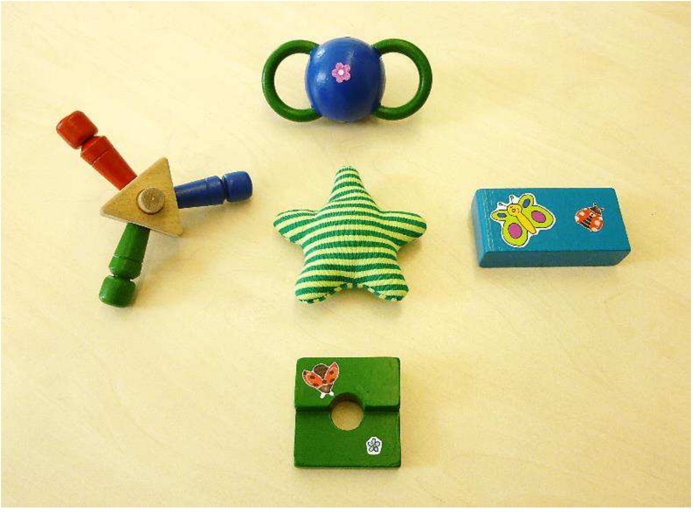
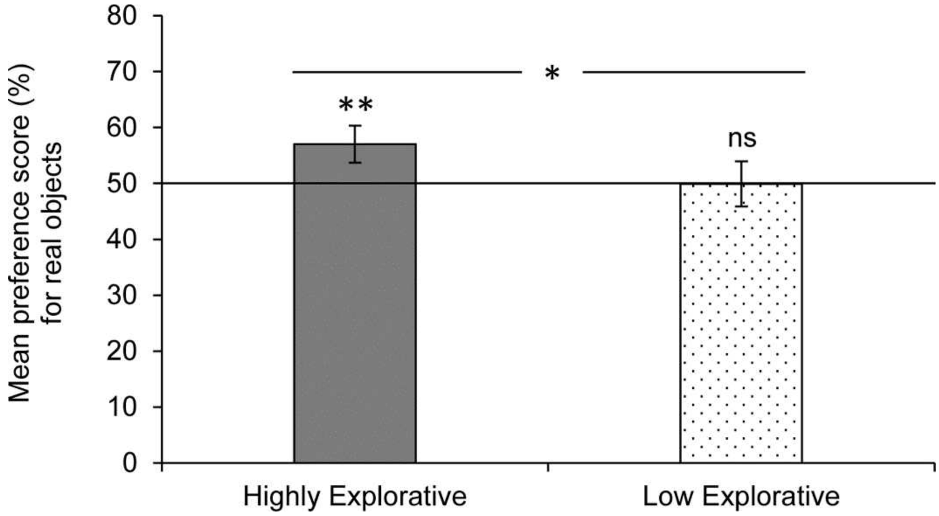


Figure 3


Mean preference score (%) for real objects
80
70
60
50
40
30
20
10
0
*
**
ns
Highly Explorative
Low Explorative

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Impact of rotation angle on crawling and non-crawling 9-month-old infants' mental rotation ability

Theresa M. Gerhard *, Gudrun Schwarzer

Department of Developmental Psychology, Faculty of Psychology and Sports Science, Justus-Liebig-University Giessen, 35394 Giessen, Germany

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The current study investigated whether 9-month-old infants' mental rotation performance was influenced by the magnitude of the angle of object rotation and their crawling ability. A total of 76 infants were tested; of these infants, 39 had been crawling for an average of 9.0 weeks. Infants were habituated to a video of a simplified Shepard–Metzler object (Shepard & Metzler, 1971), always rotating forward through a 180° angle around the horizontal axis of the object. After habituation, in two different test conditions, infants were presented with test videos of the same object rotating farther forward through a previously unseen 90° angle and with a test video of its mirror image. The two test conditions differed in the magnitude of the gap between the end of the habituation rotations and the beginning of the test rotations. The gaps were 0° and 54°. The results revealed that the mental rotation performance was influenced by the magnitude of the gaps only for the crawling infants. Their response showed significant transition from a preference for the mirror object rotations toward a preference for the familiar habituation object rotations. Thus, the results provide first evidence that it is easier for 9-month-old crawling infants to mentally rotate an object along a small angle compared with a large one.

* Corresponding author.
E-mail address: theresa.gerhard@psychol.uni-giessen.de (T.M. Gerhard).

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Introduction

For a long time, mental transformation abilities have been extensively studied in cognitive and educational research due to their predictive value regarding performances in science, technology, engineering, and mathematics (e.g., Newcombe, Uttal, & Sauter, 2013; Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). The most prominent one, mental rotation, refers to the ability to rotate mental representations of two- and three-dimensional objects (Linn & Petersen, 1985) and was first systematically examined in chronometric studies by Shepard and colleagues (e.g., Cooper & Shepard, 1973; Shepard & Metzler, 1971). In their initial experiment, Shepard and Metzler (1971) were able to show that the time to judge whether line drawings of two three-dimensional shapes portrayed the same or mirror objects increased linearly with increasing angular differences between them. The internal process underlying a decision about the spatial congruence of the object pairs was understood as being "analog" to real object rotations in three-dimensional space (see Cooper & Shepard, 1973) because the linear growth in reaction times with increasing angular disparities indicated an effect of the same spatiotemporal constraints as for real rotations.

Mental rotation ability has also been studied in infants. Moore and Johnson (2008, 2011) provided evidence that especially boys, from 3 to 5 months of age, are able to mentally rotate two- or three-dimensional objects. While findings by Quinn and Liben (2014) suggest that this advantage for male infants remains up to 9 months of age, another line of research has identified a positive link between crawling and mental rotation ability regardless of gender at that age (Schwarzer, Freitag, Buckel, & Lofruthe, 2013; Schwarzer, Freitag, & Schum, 2013). All of these studies in infants used a paradigm relatively similar to the Shepard–Metzler experiments. Infants were habituated to a stimulus and then preference tested with the habituation stimulus in a novel rotation compared with the mirror stimulus in the same novel rotation that cannot be brought into congruence by any rotation. Mental rotation was determined to have occurred when infants looked longer at the mirror stimulus because this indicates that they had recognized the habituation stimulus in the novel rotation by performing mental rotation and then preferred looking at the novel stimulus. However, these studies did not systematically test whether infants' responses to the mirror object were affected by the magnitude of the angle through which they needed to mentally rotate the stimulus, which was the crucial effect in the adult studies.

The current study was conducted to examine this effect of different rotation angles on 9-month-old infants' mental rotation ability. We also included infants' crawling ability as an independent variable due to its previously demonstrated positive influence on spatial abilities such as mental rotation.

Mental rotation ability during infancy

Evidence for precursors of mental rotation ability in infants was first provided during the 1990s by Hespos and Rochat (1997), Rochat and Hespos (1996). They examined 4- to 8-month-old infants' tracking of occluded rotational movement in order to investigate young infants' ability to generate dynamic mental representations. Infants were presented with a Y-shaped object rotating behind an occluder that covered parts of the object's movement. When the occluder was lowered at the end of the event, the object was shown in a probable or improbable orientation. Results showed that infants of all age groups looked longer to the improbable outcome, suggesting that they were able to mentally continue the object's invisible rotation and anticipate its final orientation. Moore and Johnson (2008, 2011), however, argued that these first studies differ qualitatively from studies that investigated full-scale mental rotation in older children and adults (e.g., Shepard & Metzler, 1971) because they did not use objects that are mirror images of one another (see also Quinn & Liben, 2008).

In their own mental rotation experiments, Moore and Johnson (2008, 2011) habituated 3- to 5-month-old infants to a video of a three-dimensional simplified Shepard–Metzler object rotating through a 240° arc in depth. During test trials, infants were presented with the familiar habituation object or its mirror image rotating through a previously unseen 120° angle (completing a full 360° rotation). Of the 5-month-old infants, only boys differentiated between the familiar and mirror objects (Moore & Johnson, 2008), preferring to look at the mirror object, whereas the 3-month-old boys attended longer to the familiar object (Moore & Johnson, 2011). Because novelty preferences and familiarity preferences both demonstrate infants' abilities in recognizing the familiar habituation object (e.g., Rose et al., 1982), they allow for the conclusion that both the 5- and 3-month-old boys engaged in a process of mental rotation to discriminate between the habituation and mirror object during test trials. The girls in both studies looked at the familiar and mirror objects for approximately equal durations, showing no signs of mental rotation ability. Together, these results indicated that even 3-month-old boys can mentally rotate an object in three-dimensional space and provide evidence for a gender difference in this ability.

Using a similar procedure, Schwarzer, Freitag, Buckel et al. (2013), Schwarzer, Freitag, Schum (2013) looked at the mental rotation ability of 9-month-old infants with different levels in gross and fine motor skills such as hands-and-knees crawling and manual object exploration. The authors found no gender effects but found that higher levels in both motor skills, especially crawling, resulted in longer looking times to the mirror object and, thus, in a better mental rotation performance. This idea of a link between self-produced movements and psychological development has been considered important by developmental psychologists for a long time (J. J. Gibson, 1979; Piaget, 1952). Piaget (1952) suggested that motor actions are important for infants to gain knowledge about their environment. He argued that infants' processing of objects is based on the information about objects acquired through sensorimotor experiences or actions. The significance of sensorimotor activity is likewise emphasized by ecological approaches that claim strong connections between action and perception (E. J. Gibson, 1988; J. J. Gibson, 1979) and theories on embodied cognition that assume tight links between the body and cognitive abilities (Smith & Gasser, 2005; Thelen, 2000). Regarding self-produced locomotion, Campos and colleagues have documented meaningful changes in perception, social–emotional skills, and spatial cognition with the onset of hands-and-knees crawling (for a summary, see Anderson et al., 2013; Campos et al., 2000). For example, crawling ability in infants was found to facilitate spatial object memory (Clearfield, 2004; Kermoian & Campos, 1988) and the extraction of invariance in object shape (Campos, Bertenthal, & Benson, 1980). The underlying assumption behind these findings is that rapid growth in motor skills provides infants with new opportunities for learning and acting (Adolph & Franchak, 2017).

The above-mentioned studies by Schwarzer, Freitag, Buckel et al. (2013), Schwarzer, Freitag, Schum (2013) support this line of research on the link between motor and psychological development. Together with the work by Moore and Johnson (2008, 2011), they were able to extend Rochat and Hespos's findings on rudimentary mental rotation in infants (Hespos & Rochat, 1997; Rochat & Hespos, 1996). The studies by Schwarzer and colleagues and Moore and Johnson showed that infants not only were able to mentally continue an object's rotation and anticipate its final orientation as demonstrated by Hespos and Rochat (see above) but also were able to discriminate the mentally rotated object from its mirror object as in the classical Shepard and Metzler (1971) task with adults. However, research involving systematically testing a possible effect of angular disparity on mental rotation performance in infants as it has been done in adults is extremely rare. Quinn and Liben (2008, 2014), for example, presented 3- and 4-month-old and 6- to 10-month-old infants with double presentations of the number 1, depicted in eight different angular disparities of 45° rotations from 0° to 360°, rotated in the picture plane. During familiarization trials, infants saw seven of the eight rotations in a randomized order and were then preference tested with the eighth rotation of the familiar object and its mirror image. Quinn and Liben found that in all age groups boys were more likely than girls to display a novelty preference for the mirror image in the novel orientation. Despite this gender effect, their findings also show that infants (at least the boys) were able to overcome a 45° change in the orientation of objects between the familiarization and test periods. Variations in angular disparity were also included in two studies of Frick and Möhring using the violation-of-expectation paradigm (Frick & Möhring, 2013; Möhring & Frick, 2013). In their work, 6-, 8-, and 10-month-old infants watched videos of the letter "p" or "q" moving straight down and disappearing behind an occluder. When the occluder was lowered, either the same object or its mirror image was revealed in one of five different orientations rotated in the picture plane from 0° to 180° (presented in random 45° steps). Independent of age, the authors found no effects that were elicited by the multiple rotation angles tested. Differences in infants' mental rotation performance were positively related to age and motor experiences such as prior hands-on experiences with the test objects or self-locomotion. A possible explanation for the absence of an effect of angular disparity could be that this variable was realized as a within-participant factor, and so infants saw the test events in all five orientations in random order. This may have hindered infants from mentally rotating the objects in a constant direction, which would have been necessary for isolating an effect of angular disparity.

The current study

The aim of the current study was to test the effect of rotation angle in a more systematic way by using a between-participants design and by inducing mental rotation along a certain rotation direction. In our task, all infants first saw the same geometrical object rotating through an angle of the same magnitude. After habituation to that object, in two different test conditions, infants were presented with the same object and its mirror image rotating through a novel angle. The important aspect was that the two test conditions contained a considerable increase in the magnitude of the rotation gap between the end of the habituation rotations and the beginning of the test rotations. Previous studies that used a similar design and the same kind of objects showed that it was primarily the crawling infants that were sensitive to the mirror objects (see Schwarzer, Freitag, Buckel et al., 2013; Schwarzer, Freitag, Schum, 2013). Therefore, we expected possible effects of rotation angle to emerge mainly in crawling infants; that is, we expected infants with experience in hands-and-knees crawling to show a preference for the mirror object when the gap was 0°. According to the related previous studies (see Moore & Johnson, 2008, 2011; Schwarzer, Freitag, Buckel et al., 2013; Schwarzer, Freitag, Schum, 2013), we assumed that infants would recognize the familiar object in the new rotation and prefer looking at the novel object (mirror object). When there was a gap between the end of the habituation rotations and the beginning of the test rotations, the task was supposed to get cognitively more demanding; to recognize the familiar object in the new rotation, infants needed to mentally rotate the habituation object farther from the end of the habituation rotation until it reached the beginning of the test rotations. If the infants' performance in the mental rotation task was affected by this increase in angular disparity, we expected their looking times to the mirror object to decrease. Thus, with our design, we intended to shed further light onto the process that infants engage in to solve mental rotation tasks.

Method

Ethics statement

The current study was carried out in accordance with the German Psychological Society (DGPs) research guidelines. The experimental procedure and informed consent protocol were approved of by the Office of Research Ethics at the Justus-Liebig-University Giessen. For each infant, written consent for participating in the study was obtained from the parents prior to the experiment.

Participants

The final sample consisted of 76 healthy and full-term 9-month-old infants (M = 9 months 14 days, SD = 8 days; 35 girls and 41 boys). The data from an additional 13 infants were excluded from the final sample due to fussiness ($n = 8$), excessive movement during fixation time measurement ($n = 2$), interference by parents during fixation time measurement ($n = 2$), or failure of the technical equipment ($n = 1$).

To obtain information regarding infants' crawling experience, we used a movement calendar to interview the parents (see Schwarzer, Freitag, Buckel et al., 2013). Parents were asked when their children had started to crawl, which was defined as moving in a prone position on the hands and knees for a distance of at least 2 m. In addition, parents were asked when their children had started to roll from back to belly, when their children had been able to sit independently for a minimum of 30 s, and when their children had begun to crawl on the belly for a distance of at least 2 m. In uncertain cases, we discussed the entries with the parents. However, there were no parents who expressed uncertainties concerning the time point of when their children had started to crawl, which was the motor variable of interest in this study. Bodnarchuk and Eaton (2004) previously showed that parents provide reliable reports on their infants' attainment of gross motor milestones. At the time of testing, 39 infants (18 girls and 21 boys) had been crawling on the hands and knees for an average of 9 weeks and for at least 4 weeks. According to Ueno, Uchiyama, Campos, Dahl, and Anderson (2012), infants having at least 4 weeks of crawling experience can be classified as experienced crawlers. A total of 37 infants (17 girls and 20 boys) were classified as noncrawlers. Of these 37 infants, 7 had some crawling experience of ≤3 weeks. Participants were predominantly Caucasian infants from middle-class families who lived in Giessen and its suburbs.

Stimuli

Stimuli consisted of the same three-dimensional digitized models of simplified Shepard–Metzler objects as those used by Schwarzer, Freitag, Schum, 2013—an L-object and an R-object. These two objects were mirror objects of one another and are shown in Fig. 1. The faces of the L-object were medium red when viewed from above, dark red when viewed from below, pink when viewed from the front, ocher when viewed from the back, yellow when viewed from the right, and gold when viewed from the left (even though the golden face was never visible throughout the whole experiment). The maximum horizontal and vertical dimensions of the objects during presentation were reached at 72° of the visual angle.

We constructed two habituation videos, one for the L-object and one for the R-object, as well as two familiar-object test videos with the habituation object rotating and two mirror-object test videos in which the mirror object was rotating instead of the habituation object.

The habituation videos comprised a series of forward rotations of the habituation object, each between 0° and 180° around the horizontal axis of the object. All five visible faces of the object came into view during the habituation phase over the course of rotation. Thus, infants became familiar with all used colors of the habituation object. The speed of object rotation was 18° per second. On reaching the maximum extent of rotation at 180°, the object remained in its end position for 1 s, followed by a 1-s white screen. The same forward rotation of the habituation stimulus between 0° and 180° was then started again. This procedure was repeated until infants reached the habituation criterion.

The two familiar test videos and the two corresponding mirror test videos comprised different novel 90° rotations of the objects. Characteristics concerning movement dynamics were the same for the test videos and the habituation videos; that is, on reaching the maximum extent of rotation, the object remained in its end position for 1 s followed by a 1-s white screen before this procedure was repeated. The 90° rotations of the objects in the test videos differed in their starting position from the end position of object rotations during the habituation phase (180°) by a predefined rotation gap. In Condition 1 (0° condition), test objects rotated between 181° and 271°, so that there was no gap between the end position of the habituation object and the starting position of test objects. In Condition 2 (54° condition), test objects rotated between 234° and 324°. We chose a rotation gap of 54° to make the familiar and mirror test videos different enough from the 0° condition and, at the same time, different enough from 360°, that is, the starting point of the habituation videos. Thus, the two test conditions differed by a rotation gap of 54° so as to achieve an increment in the magnitude of the angle by which the object needed to be mentally rotated (Fig. 2).

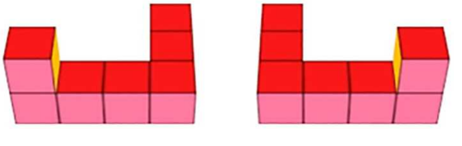

Fig. 1. Images of the simplified Shepard–Metzler objects. The L-object is displayed on the left, and the R-object is displayed on the right. The two objects are mirror images of one another.

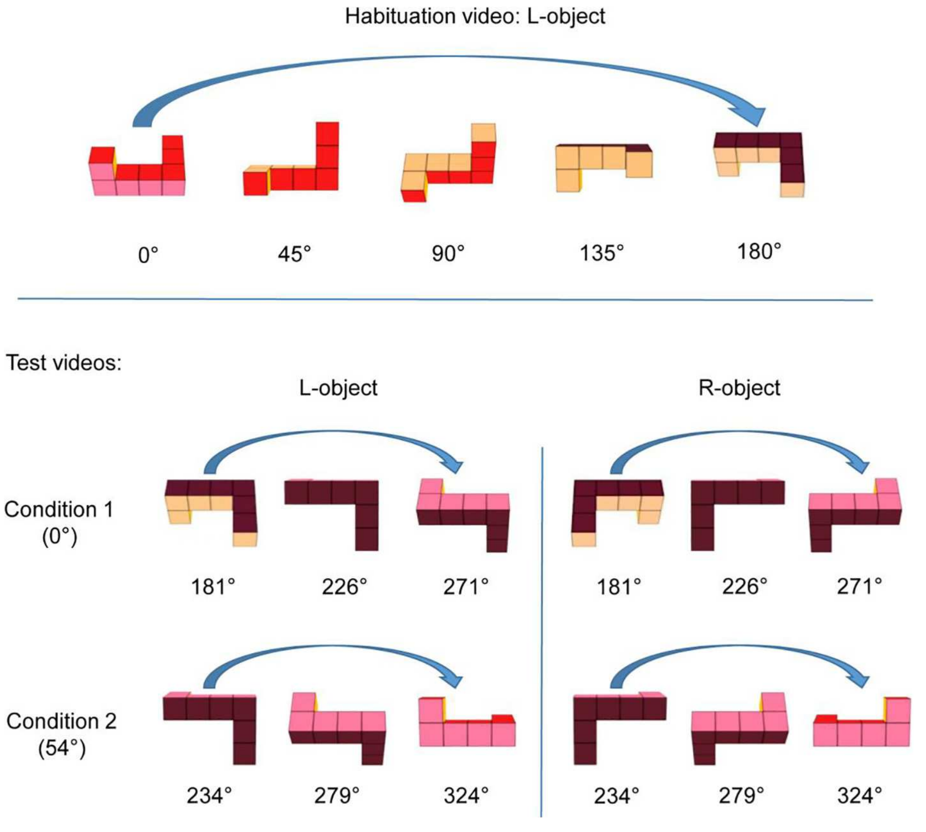

Fig. 2. Examples of the objects presented in the habituation and test videos in the two conditions. The objects in the habituation videos rotated forward repeatedly through a 180° angle. The objects in the test videos in each condition rotated forward repeatedly through a previously unseen 90° angle.

Apparatus

The experiment was conducted in a rectangular cabin with an open front to accommodate a caregiver and her child. The child was seated on the caregiver's lap at a distance of approximately 60 cm from the computer monitor screen that was inserted into the rear wall of the cabin for presenting the stimuli during the mental rotation task.

During testing, the experimenter, who was located behind the setup and hidden from view, measured infants' fixation times. The entire session was recorded on videotape using a low-light video camera that was attached to a peephole in the back of the cabin. Connected to the camera was a television screen from which infants' gaze behavior could be observed by the experimenter. Fixation time measurements were taken via a MacBook running Habit X 1.0 (Cohen, Atkinson, & Chaput, 2004), a computer software package for presenting stimuli and collecting data in habituation experiments.

Procedure

All infants were tested in individual sessions. To prevent parents from influencing their babies' fixation times, parents were asked to keep their eyes closed and to refrain from talking for the duration of the experiment.

Prior to testing, infants were allocated to one of the two test conditions (0° or 54°). The mental rotation task consisted of a habituation phase and a test phase. During the habituation phase, infants were randomly assigned to a presentation of either the L- or R-habituation video, which was counterbalanced across infants in both conditions. To attract infants' attention, the beginning of each trial was accompanied by an auditory sound. As soon as infants began fixating the stimulus, the experimenter, who was naive to the hypotheses under investigation and to the locomotion category of infants, started measuring fixation times by pressing a button. Fixation durations of less than 1 s were not counted as fixating the stimulus. Trial length was based on infants' fixation of the display. Each trial ended either 2 s after infants turned their gaze away from the stimulus or after 60 s had passed. The trial continued if infants returned their attention to the habituation stimulus during the 2-s interval. The habituation phase ended either when the average fixation time to the stimulus within the last 3 habituation trials declined to 50% of the average time within the first 3 habituation trials or when a maximum of 12 habituation trials had been presented.

The test phase included the consecutive presentation of a familiar test video and mirror test video. The order of presentation of the test videos was counterbalanced across infants in each condition.

Trained observers who were naive to the hypotheses under investigation also recorded 50% of the online encodings from the experimenter using videotapes of the sessions. The interobserver reliabilities of the online and offline observers exceeded .90 (Pearson's *r*).

Results

Habituation

Looking times during habituation, as well as the number of habituation trials, were compared in crawling and noncrawling infants in the two test conditions. For each of the two dependent variables, we calculated a two-way analysis of variance (ANOVA) with condition (0° or 54°) and crawling (crawler or noncrawler) as between-participants variables. There were no main effects of condition or crawling or any interactions of the two factors (all Fs < 1.32, all ps > .05), suggesting that crawling and noncrawling infants did not differ in their looking behavior during habituation.

Test

To test for infants' performance on the mental rotation task, a preference score on the percentage of time each infant spent fixating the mirror object (novel object) was calculated by dividing fixation time to the mirror object by overall fixation time and multiplying by 100.

A 2 × 2 × 2 ANOVA examining the effect of condition (0° or 54°), crawling (crawler or non-crawler), and gender (female or male) as between-participants variables on the preference score for mirror objects revealed no significant main effect of gender or any interactions involving gender (all Fs < 1.13, all ps > .05). Most important, however, the three-way ANOVA showed a Condition × Crawling interaction, $F(1, 68) = 11.31$, $p = .001$, partial $\eta^2 = .143$, suggesting a systematic condition-dependent change of the preferences scores only in crawling infants (Fig. 3).

To further examine the effect of angular disparity in our two motor groups, we carried out two additional one-way ANOVAs in crawling and noncrawling infants on the preference score for mirror objects, including test condition (0° or 54°) as a between-participants variable.

In crawling infants, the ANOVA revealed a main effect of condition on infants' looking behavior toward the mirror objects, $F(1, 37) = 10.83$, $p < .01$, partial $\eta^2 = .226$ (Fig. 3). A closer look at the preference scores in the two conditions showed a significant shift from a novelty preference in the 0° condition (M = 60.2%, SD = 20.4) to a familiarity preference in the 54° condition (M = 39.6%, SD = 18.8), $t(37) = 3.29$, $p < .01$, $d = 1.05$ (Bonferroni corrected). Furthermore, the preference scores in both the 0° condition, $t(18) = 2.18$, $p < .05$, $d = 0.50$, and the 54° condition, $t(19) = -2.49$, $p < .05$, $d = 0.55$, were found to be significantly different from chance level. In contrast to the crawlers, there was no effect of condition in noncrawling infants, $F(1, 35) = 2.24$, $p > .05$ (0° condition: M = 43.6%, SD = 19.5; 54° condition: M = 53.1%, SD = 19.0), indicating that angular disparity did not influence their performance in the mental rotation task.

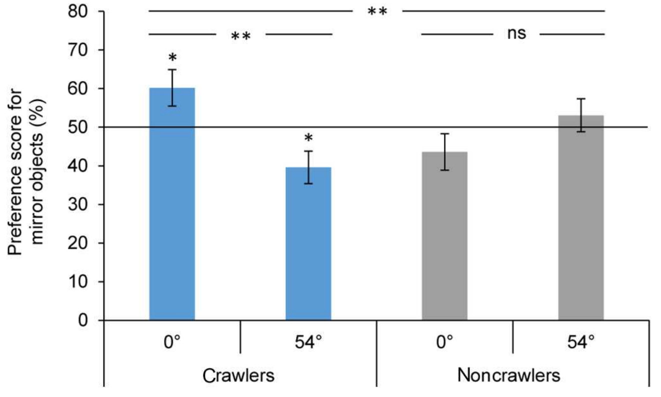

Fig. 3. Results of the test phase. Mean preference scores (%) for mirror objects in the two test conditions for crawlers and noncrawlers are shown. Error bars indicate the standard errors of the means. $^{*}p < .05$; $^{**}p < .01$; ns, nonsignificant.

Discussion

The aim of the current study was to investigate 9-month-old crawling and noncrawling infants' mental rotation of objects presented in two different rotation angles. Using this comparison, we wanted to provide new insight into the process that infants engage in when solving a task that requires mental simulation of rotational object movement such as in the original work by Shepard and Metzler (1971). Our results revealed that mental rotation performance was influenced by the magnitude of the rotation angle (i.e., by the gap between habituation and test rotations) only in the crawling 9-month-old infants. After habituation, the crawling infants' response to the test object rotations showed a significant transition from a preference for the mirror object rotations in Condition 1 (0°) toward a preference for the familiar habituation object rotations in Condition 2 (54°). Overall, these findings were in line with our expectations because the results illustrate that infants' preference for the mirror object declined as the angular difference between habituation and test object rotations was increased.

Novelty preferences are well known in the infant literature on perceptual and cognitive development (Rose et al., 1982). In the typical habituation–dishabituation procedure, novelty preferences are expected (a) when infants fully habituate to a stimulus, (b) when infants in the following test trials they are able to discriminate the familiar habituation stimulus from a novel stimulus that differs from the habituation stimulus on some critical dimension, and (c) when infants prefer to look longer at the novel stimulus (for a summary, see Nordt, Hoehl, & Weigelt, 2016; Turk-Browne, Scholl, & Chun, 2008). In our task, crawling infants in Condition 1 (0°) showed this tendency of attending to the novel objects (mirror objects). This indicates that when confronted with the familiar and mirror test objects, they were able to complete all of the steps of the recognition process. Infants recognized the familiar habituation stimulus, which led them to focus attention on the novel mirror object. By contrast, crawling infants in Condition 2 (54°) tended to look longer at the familiar habituation object. Familiarity preferences in mental rotation in infants have been observed before (Moore & Johnson, 2011; Schwarzer, Freitag, Schum, 2013). Similar to novelty preferences, familiarity preferences show infants' ability to discriminate between stimuli; however, unlike novelty preferences, they more likely emerge when infants have failed to complete the visual processing of a stimulus despite having reached the criterion for habituation (Hunter & Ames, 1988). But due to missing evidence concerning differences in habituation patterns in crawling infants in the two test conditions, our results do not point to a random incidence of incomplete habituation in Condition 2. Rather, our results more strongly support the interpretation that the entire recognition task during the test became more demanding from Condition 1 to Condition 2 because infants were forced to mentally rotate the objects for a longer distance with increasing gap angle. Thus, we propose that the infants fully habituated to the habituation stimulus in both conditions. During testing in both conditions, infants were able to recognize the habituation stimulus in the novel rotation. This process, however, was cognitively more demanding in Condition 2 than in Condition 1 because the habituation stimulus had been rotated by 54° instead of by 0°. Due to this larger cognitive effort in Condition 2, we believe that despite being able to discriminate between the mirror and familiar objects, infants were not able to show a novelty preference to the mirror object in this more demanding condition. Instead, infants indicated recognition of the familiar habituation object by increased looking to the familiar habituation stimulus in the novel rotation (54°). In Condition 1, by contrast, infants were able to more easily recognize the habituation stimulus, which was nearly the same as the habituation stimulus from the habituation phase, and used their remaining cognitive resources to study the novel stimulus, as expressed by the novelty preference to the mirror object.

In adults, similar effects of angular disparity were found by observing a positive linear relationship between response time and the rotation angle between a certain object and its mirror image (see Cooper & Shepard, 1973; Shepard & Metzler, 1971). This has been taken as evidence for the existence of an analog mental rotation strategy in adults. The dependence on the magnitude of rotation angle in our crawling infants could offer the first evidence that the process by which infants mentally rotate objects may also be analog in nature. However, some caution must be exercised when making direct comparisons between findings from infant studies and studies with older participants regarding the underlying cognitive mechanisms (Frick, Möhring, & Newcombe, 2014; Newcombe & Frick, 2010). Whereas mental rotation paradigms in adults and children usually employ reaction times as the dependent variable, findings from infant studies are mainly based on looking time measurements. However, unlike looking times, reaction-time-based responses are probably more cognitively demanding because they require processes such as decision making and explicit judgments that involve a conscious component. Frick et al. (2014) suggested that future studies with infant populations, therefore, should try to develop a method that is capable of indexing the time infants need to mentally rotate a stimulus. Another difference lies in the fact that older children and adults are typically presented with static stimuli that require the initiation of object movement, whereas most mental rotation studies in infants already show a substantial part of the movement during habituation. It can be assumed that mentally continuing such a movement is probably easier than starting it from a static state (Newcombe & Frick, 2010).

The results also fit with our expectations because previous studies showed that in mental rotation tasks it was mainly infants engaging in self-locomotion (e.g., crawling) who were sensitive to the difference between familiar and mirror objects (Frick & Möhring, 2013; Schwarzer, Freitag, Buckel et al., 2013; Schwarzer, Freitag, Schum, 2013). Note that this sensitivity was found in the current study despite alterations in procedure, that is, displaying habituation and test object rotations in a forward motion only. As outlined in the Introduction, there is a close link between self-locomotion, such as crawling, and spatial–cognitive skills (Anderson et al., 2013; Campos et al., 2000; Kubicek, Jovanovic, & Schwarzer, 2017; Kubicek & Schwarzer, in press). When infants self-locomote through a spatial layout (e.g., via hands-and-knees crawling), they are able to view objects from multiple perspectives within a particular unit of time. This may help them to internalize the experienced rotational movements associated with such motor actions. There is some theoretical and empirical work supporting the notion that such actions or motor experiences foster infants' understanding of objects because they alter what infants perceive, remember, or process regarding certain object properties (Adolph, Eppler, & Gibson, 1993; Bushnell & Boudreau, 1993; E. J. Gibson, 1988; Needham, 2000; Piaget, 1952). Such actions and experiences also alter what infants attend to; because crawling provides infants with the opportunity to explore their environment (Schwarzer, 2014) and act on it in a self-initiated manner (Anderson et al., 2013), it demands focused attention to object arrays and spatial layouts. Walk (1981) even argued that it is not motor activity itself that is crucial for spatial–cognitive development but rather its entailing requirement for properly directing attention to the spatial layout. Nevertheless, although attention ensures that the information associated with motor experiences is processed more deeply and perhaps more elaborately, the experience itself and the visual information it provides will always be foremost. As infants learn to crawl and move their bodies through the environment, the spatial layout of the environment comes to the fore as crucially relevant information. It can be assumed that it is this particular type of visual experience, produced by crawling, that enhances infants' mental rotation ability.

However, one might still ask why our noncrawlers were not able to mentally rotate the objects, especially when there was no gap between habituation and test object rotations. In previous studies, even younger 3- to 5-month-old male infants showed this ability (Moore & Johnson, 2008, 2011). Although the studies by Moore and Johnson (2008, 2011) used a comparable testing design, there are some methodological variations between our studies that can account for the difference in results. Moore and Johnson presented their simplified Shepard–Metzler objects in a vertical rotation, which seems to appear more frequently in the natural environment than the horizontal rotations used in our study (Schwarzer, Freitag, Buckel et al., 2013). More important, there are differences in the extent of object rotations that infants were presented with. In contrast to Moore and Johnson (2008, 2011), who showed a 240° rotation of the objects during habituation (see also Schwarzer, Freitag, Buckel et al., 2013; Schwarzer, Freitag, Schum, 2013), infants in the current study saw the habituation objects rotating through an angle of only 180°. Moreover, test object rotations in this study covered only an additional 90° compared with the above-mentioned studies that showed test objects rotating through the remaining 120° (completing a full 360° rotation). It can be assumed that these differences in the visual input, particularly during habituation, not only made the formation of a solid mental object representation more difficult, which is a crucial precondition for dealing with such tasks, but also made it harder for infants to distinguish between familiar and novel test objects during test trials.

Additional limitations of this study are that, first, we cannot provide information about the developmental course of mental rotation ability in infants because the factor of age was held constant in our design and the infants were classified as those with or without crawling experience. This makes it difficult to argue unequivocally that crawling experience is what led some infants to show evidence for mental rotation, whereas other infants did not show evidence of this ability. It is possible that a third factor contributes to the relationship between crawling and mental rotation, meaning that whatever led some infants to be advanced in the acquisition of crawling also led to an advancement of skill in mental rotation. An appropriate experimental design to overcome this limitation is to randomly assign pre-locomotor infants to receive some kind of self-produced locomotor experience (Uchiyama et al., 2008). Second, although crawling infants' performance was impeded by the different rotation angles of the test stimuli, we cannot definitively answer whether infants were in fact engaged in a process of analog mental rotation or not. As discussed above, to clearly indicate analog mental rotation in infants, it would probably require the employment of a method that can index the time infants need for mentally rotating a stimulus such as reaction times as measured in adults. In addition, other factors could be responsible for the obtained results, for example, that the test objects' shape and color in Condition 1 (0°) were overall more similar to the appearance of the habituation object in its rotational end position compared with those in Condition 2 (54°), although no new colors came into play in the test rotations. In future research, the objects could be altered in such a way that the different faces of the objects are of the same color. Still, one must not disregard the fact that the distinct coloring of the objects' faces probably serves as an important spatial cue for the infants. Aligning them, therefore, could make the task too difficult, leading to floor effects. Finally, future research should attempt to change the disparity in rotation angles more gradually so as to detect the precise angle at which infants start to fail in the task.

In conclusion, our findings show for the first time that crawling 9-month-old infants' mental rotation performance is influenced by the magnitude of rotation angle. With due caution, this could be interpreted as a first sign of an analog mental rotation process in infants.

Acknowledgments

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