UNIVERSIDAD COMPLUTENSE DE MADRID

FACULTAD DE PSICOLOGÍA

TESIS DOCTORAL

Mecanismos cognitivos y neurales de la organización perceptiva

Cognitive and neural mechanisms of the perceptual organization

MEMORIA PARA OPTAR AL GRADO DE DOCTORA

PRESENTADA POR

Cristina Villalba García

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José Antonio Hinojosa Poveda
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Cristina Villalba García

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COGNITIVE AND NEURAL MECHANISMS OF THE PERCEPTUAL ORGANIZATION

Cristina Villalba García

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Pedro Raúl Montoro Martínez.
María Dolores Luna Blanco.

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DECLARACIÓN DE AUTORÍA Y ORIGINALIDAD DE LA TESIS PRESENTADA PARA OBTENER EL TÍTULO DE DOCTOR

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estudiante en el Programa de Doctorado en Psicología RD99/2011,
de la Facultad de Psicología de la Universidad Complutense de Madrid, como autor/a de la tesis presentada para la obtención del título de Doctor y titulada:

'Mecanismos cognitivos y neurales de la organización perceptiva'

y dirigida por: José Antonio Hinojosa Poveda, Pedro Raúl Montoro Martínez, María Dolores Luna Blanco.

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Dedicada a Ismael,
mi padre.

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Resumen

Mecanismos cognitivos y neurales de la organización perceptiva

1. Introducción

Las operaciones de agrupamiento perceptivo son esenciales tanto para procesar escenas visuales como para reconocer objetos. Estas operaciones se han denominado como las *leyes del agrupamiento perceptivo*, siendo postuladas a principios del siglo pasado por Wertheimer (1923). Estas leyes hacen referencia a la proximidad, la semejanza, el destino común, el cierre o la buena continuación entre elementos. Así pues, estos factores han sido propuestos como aquellos que guían a nuestra percepción a organizar los elementos que dan lugar a la escena visual. Posteriormente, la investigación en este campo ha continuado desarrollándose, resultando en la formulación de nuevas leyes, como la región común o la conexión (véase Brooks, 2015, para una revisión).

El estudio de la interacción entre diferentes factores de agrupamiento es fundamental, ya que supone una representación más fidedigna de cómo percibimos los entornos en los que múltiples factores compiten por guiar nuestra percepción y atención (Peterson y Kimchi, 2013). Sin embargo, aún no existe una teoría integrada del agrupamiento perceptivo, quizás debido a la gran diversidad de métodos y la escasez de medidas cuantitativas (Jäkel et al., 2016). El estudio de la convergencia entre distintas medidas de agrupamiento perceptivo es crucial si consideramos que investigaciones recientes han señalado que en estas operaciones están involucrados diferentes subsistemas de visión (Schmidt y Schmidt, 2013). Asimismo, es relevante examinar la dinámica cerebral de estas interacciones, para lo que el uso de técnicas como los potenciales eventorelacionados (PERs) puede ser beneficioso, ya que proporcionan información precisa sobre el momento en particular en el que distintos principios de agrupamiento interactúan (Montoro et al., 2015).

2. Objetivos

El objetivo principal de la presente tesis doctoral reside en examinar los mecanismos cognitivos y neurales implicados en los procesos de la organización perceptiva en la modalidad visual.

El **Estudio Experimental I** tiene como objeto examinar los correlatos cerebrales relacionados con la competición entre dos principios gestálticos clásicos, en concreto, entre la proximidad y la semejanza en forma, registrando PERs. Solo un estudio ha investigado los correlatos cerebrales de la interacción entre estos factores, en concreto la cooperación entre ambos, sin que haya sido posible determinar la contribución de cada uno de estos factores a la interacción entre ellos (Han, 2004). Para subsanar esta limitación, se hará uso de un paradigma experimental que permitirá examinar la contribución de cada principio de agrupamiento de manera individual a la competición entre ambos (Luna et al., 2016).

El objetivo del **Estudio Experimental II** es investigar los procesos de competición entre diferentes factores del agrupamiento perceptivo mediante una tarea indirecta (tarea de discriminación de la repetición, TDR, Palmer y Beck, 2007). Se examinarán las interacciones entre proximidad y semejanza en luminancia **(Experimento 1)** y las interacciones entre región común y conexión **(Experimento 2)**. La novedad de este estudio radica en la inclusión de una nueva tarea de igualación objetiva de la fuerza o grado de los principios de agrupamiento, con el fin de ajustar para cada participante la fuerza de ambos principios con anterioridad a la realización de la TDR.

3. Resultados

En el **Estudio Experimental I**, los resultados mostraron que las condiciones simples, en las que los principios se presentaban aisladamente, fueron respondidas con mayor rapidez y precisión que las condiciones de competición. Se encontró una ventaja para la condición simple de proximidad en comparación con la condición simple de semejanza en forma. Sin embargo, la interferencia hallada entre ambos factores en la condición de competición fue bidireccional y asimétrica, ya que la semejanza en forma interfirió más sobre la proximidad que viceversa. En cuanto a los PERs, no se encontraron diferencias entre principios en el componente P100, lo que sugiere que el procesamiento temprano de ambos factores comparte operaciones similares iniciales. Posteriormente, ambos principios (proximidad y semejanza en forma) interactuaron en la ventana temporal del componente N200: la condición simple de semejanza se asoció a una mayor amplitud que la condición de competición mientras que no hubo diferencias entre estas dos condiciones en el caso del principio de proximidad. Este hallazgo podría reflejar la saliencia visual y/o la fluidez de procesamiento relativa al principio de semejanza en forma. Finalmente, el hallazgo de mayores amplitudes asociadas a las condiciones simples en comparación con las condiciones de competición en la ventana temporal del componente P300 encontrado, parece estar relacionado con la confianza en la toma de decisiones durante la selección de la respuesta.

En el **Estudio Experimental II**, los resultados mostraron que las condiciones simples se respondían más rápido que las condiciones de competición en ambos experimentos. En el **Experimento 1**, se encontró un efecto de interferencia bidireccional y asimétrica, ya que el principio de semejanza en luminancia interfería más sobre el principio de proximidad que viceversa. De manera similar, en el **Experimento 2** nuestros resultados indicaron que la región común dominó la organización perceptiva del patrón visual. Cabe destacar que solo algunos participantes (56 y 10 participantes, respectivamente) lograron igualar la fuerza de agrupamiento de ambos principios en la fase de igualación objetiva previa a la tarea experimental en ambos experimentos.

4. Conclusiones

En la presente tesis se ha profundizado en la caracterización de los mecanismos que subyacen a la competición entre distintos principios de agrupamiento perceptivo.

En el **Estudio Experimental I**, se ha examinado el curso temporal de los mecanismos cerebrales involucrados en la interacción entre dos principios de agrupamiento clásicos mediante el registro de PERs. Como hallazgo principal, se ha identificado al componente N200 como un índice neural sensible a la competición entre estos dos factores.

En el **Estudio Experimental II**, a pesar de las diferencias individuales encontradas en los tiempos de reacción en las condiciones simples de los distintos principios subyacentes en la tarea de discriminación de la repetición, el patrón general de respuesta en las condiciones en las que ambos principios competían, fue común para toda la muestra, de forma que los principios de semejanza en luminancia y región común dominaron la organización perceptiva de los patrones estimulares cuando compitieron con proximidad y conexión, respectivamente.

Abstract

Cognitive and neural mechanisms of the perceptual organization

1. Introduction

Perceptual grouping operations are essential to process visual scenes as well as to recognize objects. These operations have been called the *laws of perceptual grouping*, being postulated at the beginning of the last century by Wertheimer (1923). These laws refer to proximity, similarity, common fate, closure or good continuation between elements, which has been proposed as factors that guide our perception to organize the elements that give rise to our visual scene. In recent years, subsequent developments in this field of research have allowed the study and formulation of new perceptual grouping laws, such as common region or connectedness (see Brooks, 2015, for a review).

The study of the interaction between different grouping factors is essential, as it supposes a more reliable representation of how we perceive environments in which multiple factors compete to guide our attention (see Peterson & Kimchi, 2013, for a review). However, an integrated theory of perceptual grouping operations is still lacking, perhaps due to the great diversity of methods and a shortage of quantitative measures (Jäkel et al., 2016). The study of the convergence between different measures of perceptual grouping is crucial if we consider the results from recent studies showing that different subsystems of vision are involved in these operations (Schmidt & Schmidt, 2013). It is also relevant to examine the temporal brain dynamics of these interactions. In this sense, the use of techniques such as event-related potentials (ERPs) could be of some

help, as they provide precise information about the temporal course of the interaction between grouping principles (Montoro et al., 2015).

2. Objectives

The main goal of the present doctoral thesis is to examine the cognitive and neural mechanisms involved in the processes of perceptual grouping organization in visual modality.

The **Experimental Study I** aims to examine the neural correlates involved in the competition between two classic Gestalt laws, in particular, between proximity and shape similarity cues. For this, ERPs will be registered. Only a previous study has examined these cerebral correlates of the interaction between both grouping factors. However, Han (2004) examined only cooperative interactions. Also, the contribution of each single factor to the interaction it could not be quantified. To overcome this limitation, we will use an experimental paradigm to examine the contribution of each single grouping principle to the competition between them (Luna et al., 2016).

The **Experimental Study II** intends to examine the competition between different perceptual grouping factors by means of an indirect task (*Repetition Discrimination Task*, RDT, Palmer & Beck, 2007). The interactions between two classical laws - proximity and similarity in luminance - **(Experiment 1)** and the interactions between two extrinsic cues- common region and connection - **(Experiment 2)** will be examined. The novelty of our study lies in the inclusion of a new objective equating task, in order to individually adjust the previous strength of grouping of both principles prior to the performance of the RDT.

3. Results

In **Experimental Study I**, our results showed that single conditions were responded faster and more accurately than competing conditions. Additionally, an advantage effect was found for proximity single conditions compared to shape similarity single conditions. However, the interference effect found between both factors was bidirectional and asymmetric, as shape similarity cues interfered more over proximity cues than vice versa. Regarding ERPs, no differences were found in P100 component, which may be related to contour interpolation operations, necessary for perceptual completion of geometric elements contained in both shape similarity and proximity competing conditions. Subsequently, both principles interacted in the N200 component, where shape similarity single cues elicited large positive amplitudes while competing conditions are associated to a more negative amplitude. However, no differences in amplitude were found in proximity grouping conditions. Thus, our N200 component, could be interpreted as a brain index of the visual salience and/or the processing fluency of shape similarity grouping cues. Finally, we found greater amplitudes for single conditions compared to competing conditions in the P300 component, which seems to be associated to decision-making processes during response selection.

In **Experimental Study II**, our results showed that single conditions were responded faster than competing conditions in both experiments. In **Experiment 1**, a bidirectional and asymmetric interference effect was found, as luminance similarity cues interfered more over proximity cues than vice versa. Similarly, in **Experiment 2** our analyses indicated that common region cues dominated over connectedness cues. It should be noted that only some participants managed to match the grouping strength of both principles in the objective equating phase (56 participants, Exp. 1; 10 participants, Exp. 2) prior to RDT in both experiments. However, even those participants who showed similar RTs for both single conditions in the objective equating task also displayed a processing advantage for common region (shorter RTs).

4. Conclusions

The present doctoral thesis aimed at characterizing the mechanisms that underlie the competition between multiple principles of perceptual grouping.

In **Experimental Study I**, the temporal course of the brain mechanisms involved in the interaction between two classic grouping principles by recording ERPs has been examined. As a main finding, the N200 component has been identified as a first index sensitive to the competition between these two factors.

In **Experimental Study II**, individual differences were found in reaction times regarding single conditions in the visual search task. However, the overall pattern of response (RTs) in competing conditions (RDT), was common for the entire sample of participants.

Publications

- **Villalba-García, C.**, Santaniello, G., Luna, D., Montoro, P. R., & Hinojosa, J. A. (2018). Temporal brain dynamics of the competition between proximity and shape similarity grouping cues in vision. *Neuropsychologia*, *121*, 88-97.

Other publications related to this doctoral thesis:

- Montoro, P. R., **Villalba-García, C.**, Luna, D., & Hinojosa, J. A. (2017). Common region wins the competition between extrinsic grouping cues: Evidence from a task without explicit attention to grouping. *Psychonomic bulletin & review*, *24*(6), 1856-1861.

- Luna, D., **Villalba-García, C.**, Montoro, P. R., & Hinojosa, J. A. (2016). Dominance dynamics of competition between intrinsic and extrinsic grouping cues. *Acta psychologica*, *170*, 146-154.

Abbreviation list

Ag: Silver.

AgCl: Silver chloride.

cd: Candela.

cm: Centimeter.

CN: Connectedness.

Comp.: Competitive.

Coop.: Cooperative.

CR: Common Region.

d.f.: Degrees of freedom.

dB: Decibel.

diff.: Differential.

e.g.: Exampli gratia.

Exp.: Experiment.

Fig.: Figure.

Hz: Hertz.

i.e: Id est.

in: Inches.

Interf.: Interference.

kHz: Kilohertz.

LU: Luminance similarity.

m^2: Square meter.

mm: Millimeter.

ms: Milliseconds.

MSe: Mean Squared error.

n.s.: No significant.

º v.a.: Degrees of visual angle.

oct: Octave.

pag.: Page.

PR: Proximity.

t: Time.

v.: Version.

vs.: Versus.

µV: Microvolt.

Acronyms list

ACC: Accuracy.

ANOVA: Analysis of variance.

EEG: Electroencephalography.

EOG: Electrooculography.

ERPs: Event-related potentials.

FEDER: Fondo Europeo de Desarrollo Regional.

GG: Greenhouse-Geisser.

GOC: grouping operating characteristics maps.

ICA: Independent component analysis.

LCD: Liquid crystal display.

LED: Light-emitting diode.

M: Mean.

MINECO: Ministerio de Economía y Competitividad.

PCA: Principal component analysis.

RDT: Repetition discrimination task.

RGB: Red, green, blue.

RT: Reaction time.

SD: Standard deviation.

SF: Spatial factor.

sPCA: Spatial principal component analysis.

TF: Temporal factor.

tPCA: Temporal principal component analysis.

UNED: Universidad Nacional de Educación a Distancia.

Symbol list

%: Percentage.

F: Fisher's F.

kΩ: Kiloohm.

n: Sample size.

η_p^2: Partial eta-square .

p: P-value or probability value.

Δ: Incremental change in a variable.

Figure List

Introduction

Figure 5. Example of dot lattices observed by participants in tasks such as the one designed by Oyama (1961). These matrices have been used in different studies devoted to quantify proximity grouping cues. **(A)** When distances between dots are equivalent in both rows and columns (between vectors *a* and *b*) the probability that participants perceive rows and columns is the same. **(B)** However, when distances are manipulated (*b*) changes in relation to the other (*a*), the strength of the shortest distance is predicted by a negative power function. p. 64

Figure 6. Examples of stimuli taken from Kubovy and van den Berg studies (2008). Dots with the same contrast were arranged along the longer axis (similarity versus proximity in competition) or arranged along the shorter axis of each rectangle of dots within the lattice (similarity and proximity in conjunction). p. 66

Figure 7. Examples of stimuli used in Quinlan and Wilton experiments (1998). **(A)** Pattern not grouped. **(B)** Grouping by shape similarity. **(C)** Grouping by proximity. **(D)** Cooperation between proximity and grouping by shape similarity cues. **(E)** Competition between proximity and shape similarity cues. p. 68

Figure 8. Examples of stimuli used by Luna et al. (2016). Experiment 1: **(A)** Single Proximity **(B)** Single shape similarity **(E)** Competition between proximity and shape similarity cues. Experiment 2: **(B)** Single common region **(C)** Single connectedness **(F)** Competition between common region and connectedness cues. Experiment 3: **(C)** Single common region **(D)** Single shape similarity **(G)** Competition between common region and shape similarity cues. The target was always the central element of a row of seven geometric figures that could be grouped with the three elements located on its right

Experimental Study I

Table List

Experimental Study I

Experimental Study II

1. Introduction

Our ability to perceive the world that surrounds us it is something that almost all of us take for granted. As Palmer (1999) has stated : *"We just open our eyes and look! When we do, we perceive a complex array of meaningful objects located in three-dimensional space"* (Palmer, 1999, p. 4). When we observe our visual environment, the visual scene is composed of multiple pieces. From this image several sources of information are extracted, such as colour, shape, size, and so on. These sensorial features seem to interact with each other, whose organization is crucial to achieve a consistent and stable representation of our environment.

In 1923, Max Wertheimer already thought over about this issue and consequently he postulated the *laws* of perceptual grouping. The development and study of these laws could constitute a suitable approach that guides us to a better understanding of how sensory information is organized to perceive people, animals or objects. In fact, our system constantly processes sensory inputs, whose information must be organized to give rise to a congruent and veridical representation of the real or external world (Pomerantz & Kubovy, 1981) in which we are immersed. It should be noted, although multiplicity of processes are involved in the configuration of these images, we finally perceive a stable and accurate visual world, even in spite of processing ambiguous and noisy information.

In following sections, the so-called "confetti issue" will be introduced and, then, the Gestalt laws will be described from its origins. Similarly, it will delve into methodological foundations. And finally, four different approaches related to perceptual grouping operations will be briefly discussed.

1.1. The confetti issue.

What we perceive daily could be defined from a metaphorical point of view as *"a snowstorm of swirling, multi-coloured confetti resulting from the output of millions of unrelated retinal receptors"* (Palmer, 1999, p. 255). The electromagnetic energy received by our millions of photoreceptors located in the retina is light emitted from each object embedded in the visual environment. As a consequence, this energy renders an image in the retina, which consists of a two-dimensional distribution of light of different intensities and wavelengths. A priori, the information contained in the retinal image is not organized per se, consequently it could be said that it is ambiguous as this image does not contain objects as we perceive them. Therefore, how can we sure if the objects perceived are an exact reflection of the elements of real world from information contained in our retinal image? One proposal to solve this question suggests the principles of perceptual grouping as those laws or instructions that tell our system what goes with what in this retinal mosaic or "confetti". Hence, unravel these mechanisms underlying perceptual grouping cues could be decisive to better understand the phenomenon of vision itself, as Coren, Ward, and Enns (1999) already pointed out, our perceptual system is guided by an urgent need to organize the elements of the environment. Next, the emergence of these laws will be described, as well as, these grouping factors will be detailed in more depth.

1.2. Gestalt Laws of Perceptual Organization.

The classic laws of perceptual grouping were originally proposed and described by Wertheimer (1923). The formulation of these laws was motivated by the observations made by Wertheimer about our perceptual experience of the world. In his own words: *"I stand at the window and see a house, trees, sky. Theoretically I might say there were 327 brightnesses and nuances of colour. Do I have "327"? No. I have sky, house, and trees. It is impossible to achieve "327" as such."* His pioneering investigations led to establish a set of rules that specify the way in which we organize or configure the essential elements of the environment into a whole or as he called "Gestalt".

The German word "Gestalt" can be translated by "*configuration*" or "*good form*". Gestalt psychology pointed out a series of fundamental problems in the field of perception, such as the study of segregation and the grouping of elements in our visual environment (for an extensive review, see Wagemans et al., 2012a). Gestalt Psychology emerged in opposition to the ideas of structuralists (Titchener, 1905; Wundt, 1879), which conceived our object perception as a result of the sum of different separate sensations. In contrast, Gestalt psychologists assumed that the properties of the whole perceptual field are different from the sum of their constituents. Thus, they were interested in the mechanisms that governed the organization and segregation of elements in our environment (Koffka, 1935; Köhler, 1938). The Gestalt school was strongly criticized since its main assumptions were based in phenomenological descriptions. However, in the 70s of the 20st century, observations from several studies lead to a revival of some of the conceptual ideas developed by the Gestalt psychologists. For instance, Pomerantz and Garner (1973) observed that the configuration of stimuli modulates the ability to selectively attend to each element distinctively. Also, Navon (1977) studied global precedence in hierarchical letters. It is worth mentioning that hierarchical structures were also studied in the context of perceptual representations (e.g., Palmer, 1977).

1.2.1. Classical Gestalt Laws of Perceptual Grouping.

Wertheimer (1923) first formulated five classic laws of perceptual grouping: proximity, similarity, good continuation, closure and common fate. In his pioneering studies, Wertheimer used a simple row of equally spaced dots (see Figure 1A). When he first manipulated the distance between these dots, he realized that when two elements were closer to each other (and at the same time segregated from adjacent ones) they tended to be perceived as perceptual groups. This is how he formulated the principle of proximity.

Wertheimer manipulated different dimensions of discrete elements in uniform arrays and observed how these manipulations impacted the organization of the final array. Based on these observations, he formulated the following laws that guide perceptual organization:

I. Law of proximity: Discrete units or elements that are spatially close to each other tend to be perceived as a group (see Figure 1B).

II. Law of similarity: Discrete units or elements that share features (such as their luminance, colour, shape, size or orientation) tend to be perceived as a group (see Figure 1C, 1D, 1E, 1F, 1G).

III. Law of good continuation: There is a tendency to perceive soft instead of pronounced changes in the environment. The observer tends to complete smooth trajectories beyond their end points (see Figure 1I).

IV. Law of closure: This law describes the preference for perceiving closed forms as opposed to open forms. It reflects the bias to complete forms even when part of the information is missed (see Figure 1J).

V. Law of common fate: Elements that follow the same pattern of movement tend to be perceived as part of the same perceptual group (for example, several dancers in choreography; see Figure 1H). Wertheimer already observed the dynamic properties of this law, also called "uniform destiny".

Classical principles of perceptual grouping

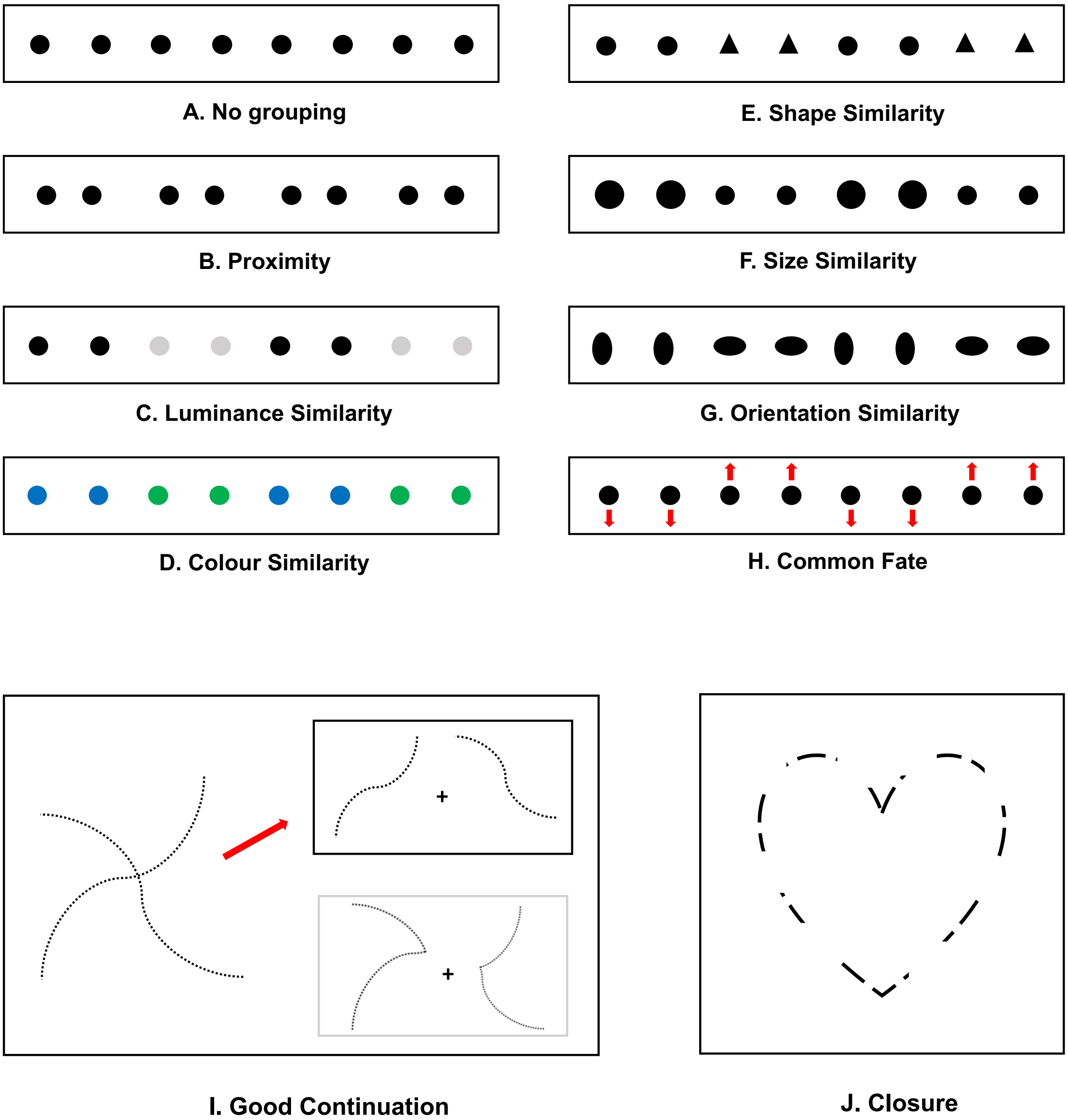


Figure 1. Classical principles of perceptual grouping. **(A)** No grouping. **(B)** Proximity. **(C)** Luminance Similarity. **(D)** Colour Similarity. **(E)** Shape Similarity. **(F)** Size Similarity. **(G)** Orientation Similarity. **(H)** Common Fate. **(I)** Good Continuation. **(J)** Closure. Adapted from Palmer (1999).

Despite of the formulation of these perceptual laws, Wertheimer (1923) also developed the Principle of Prägnanz, which also is called “Law of simplicity”. Based on the economy concept of Ockham's razor, this principle states that every visual pattern tends to be perceived according to the simplest or most basic interpretation. Although other Gestalt psychologist were interested in this principle (Koffka, 1935; Köhler, 1938) a well-defined theory of Prägnanz law has been never established. In Figure 2, we can observe different configurations that would compete between them. Our visual system would quickly resolve this conflict by determining which solution provides us "the best Gestalt". This concept has been adopted by modern information theories of vision. The idea underlying here is based on the fact that the organization that require less information to be computed is preferred to those that need more processing resources (e.g., Hochberg & McAlister, 1953).

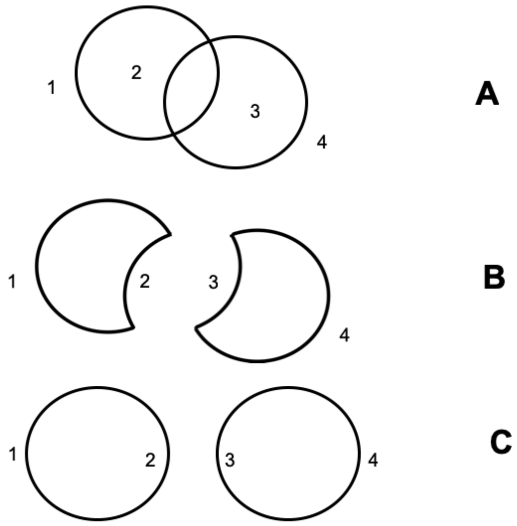


Figure 2. In image **(A)** elements can be organized in different and multiple ways. One interpretation could be the one displayed in image **(B).** However, the most probable explanation to which our visual system arrives is to image **(C)** this is how Prägnanz principle operates.

1.2.2. New Gestalt Laws of Perceptual Grouping

In the 90s of the 20th century, vision researchers proposed new Gestalt laws of grouping such as *common region* (Palmer, 1992), *element connectedness* (Palmer & Rock, 1994b), *synchrony* (Alais, Blake, & Lee, 1998), *uniform connectedness* (Palmer & Rock ,1994b) or *generalized common fate* (Sekuler & Bennett, 2001). Some of these laws reflect variations of the classical laws, while others describe completely new concepts. Grouping factors since Palmer's proposal (1992, 1999) can be classified into two broad categories or cohorts: (I) *intrinsic principles*, based on built-in properties of discrete elements (as their position or size) and (II) *extrinsic principles*, based on relationships between unrelated elements or units and other external elements that induce them to group. Classic Gestalt laws would be considered as *intrinsic grouping cues*, while common region or connectedness cues would be suggested as *extrinsic grouping cues*.

These most relevant new principles of perceptual grouping can be summarized as follows:

I. Principle of common region: Elements or units located within the same bounded region tend to be grouped (see Figure 3A). Common region seems to have an ecological foundation arising from hierarchically embedded parts (e.g., leopard's spots or the characteristics relating to faces; Palmer, 1992).

II. The principle of element connectedness: the units or elements that are physically connected by a third element, tend to be perceived as a group (see Figure 3B). As common region cues, the rationale behind connectedness cues has an ecological sense (Peterson, 1994), as different parts that compose an object tend to be connected to each other (Brooks, 2015).

III. The principle of synchrony: Elements or units that change at the same time tend to be perceived as a group (see Figure 3C) (Alais, Blake, & Lee, 1998). Synchrony and common fate (described in previous section) are two dynamic principles. However, the principle of synchrony does not imply movement, only simultaneous changes in the features of the elements, such as colour or size.

IV. The principle of uniform connectedness: Units or elements that are connected by uniform visual properties (such as luminance, colour, texture, motion or depth) tend to be perceived as related elements (Palmer & Rock, 1994b).

V. Generalized common fate: It is a variation of the common fate principle proposed by Wertheimer (1923), which could be understood as *"common fate for luminance"* as the elements or units do not move through physical space but they do move through luminance features (Sekuler & Bennett, 2001). The formulation of this principle was based on ecological observations. For instance, it is usual to perceive changes in the levels of illumination of a scene in which different areas of an image can be darkened or lightened simultaneously, such as natural lights and shadows (van den Berg, Kubovy, & Schirillo, 2011).

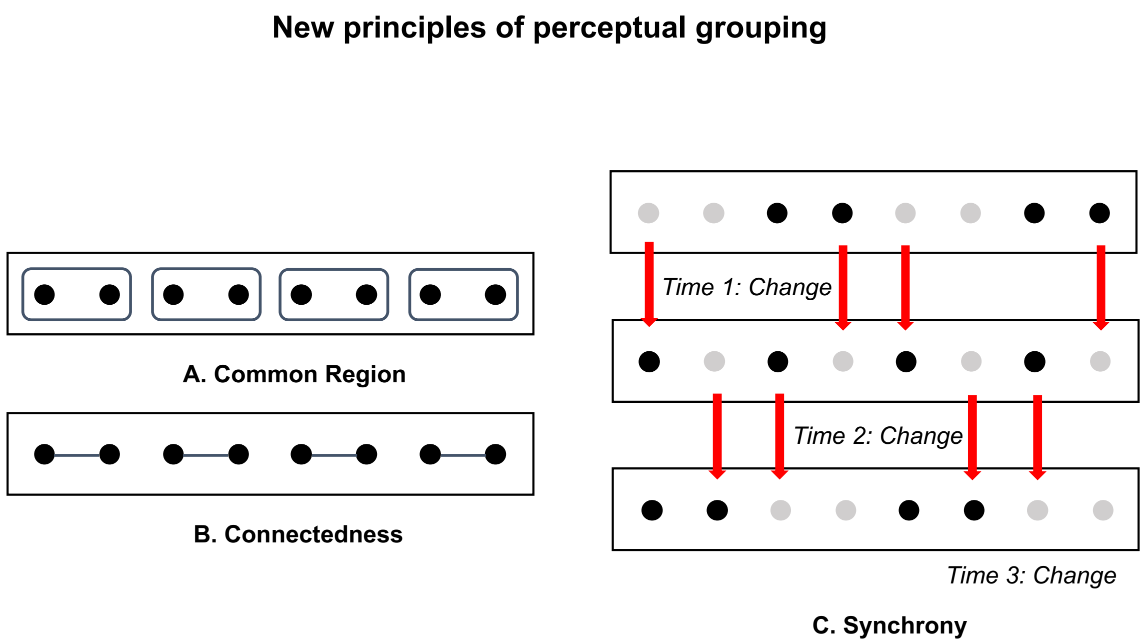


Figure 3. Examples of new principles of perceptual grouping. **(A)** Common Region. **(B)** Connectedness. **(C)** Synchrony. Adapted from Palmer (1999).

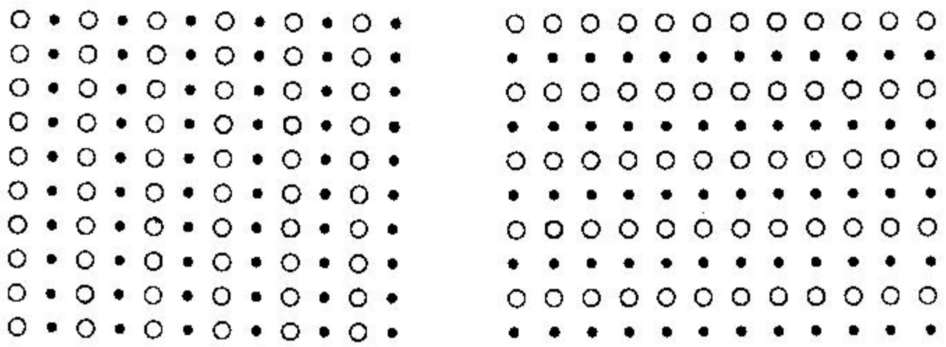
1.3. Study of perceptual grouping laws in the visual system.

For decades, the laws of perceptual grouping have been criticised for being poorly described and imprecise (e.g., Hochberg, 1974). A main criticism concerns the lack of quantitative methods (e.g., Jäkel et al., 2016) since first formulations were based on phenomenological demonstrations (e.g., Albertazzi, 2013). To overcome this limitation, quantitative approaches have been developed during the last decades (e.g., Beck & Palmer, 2002; Kubovy & Wagemans, 1995; Pomerantz & Garner, 1973).

Phenomenological judgments have been considered as a direct measure of perceptual grouping operations, as subjective reports allow registering spontaneous perception (e.g., Strother, van Valkenburg, & Kubovy, 2003). In contrast, no objective and quantifiable measure of perceptual grouping could be collected with phenomenological descriptions. Perceptual judgments could be biased by prior knowledge (observer bias) or experimental instructions (investigative bias). Palmer and Rock (1994a) have considered that phenomenological judgments could be quantitative since the manipulation of a pattern organization could be considered as an independent variable, while these judgments would be a dependent variable. In fact, the proportion of the observers that reported different perceptual organizations could be considered a quantitative measure (Rock, Nijhawan, Palmer, & Tudor, 1992). On the other hand, Shepard, Kubovy and Pomerantz (1981) considered perceptual grouping as an operation exerted on the stimuli and, consequently, its effects should modulate reaction times or response accuracy rates, which let to obtain a systematic and quantifiable measures of perceptual grouping operations. However, this approach also has its disadvantages as it is based on indirect data, as perceptual grouping operations are only reported through its influence on the participant's performance. Likewise, observers are forced to choose only one among all possible visual configurations generated. Similarly, assorted quantitative methods have been developed up to the present (see Kimchi, 2015 or Pomerantz & Cragin, 2015, for reviews).

The perceptual result of processing of a stimulus integrates different visual cues. A fundamental question is how these cues are related in an image: do these different grouping cues cooperate or compete against others? Phenomenological demonstrations first attempted to study these laws. However, firm conclusions can be established only if these laws operate *"under ceteris paribus"* conditions. This is a well-known limitation in the study of these perceptual grouping principles. In fact, due to these "*ceteris paribus*" rules it is difficult to predict the combined effects of multiple competing grouping cues acting in the same display, as only is possible to predict the perceived configuration while "other things remain equal" (Palmer, 1999).

Despite the aforementioned limitation, in pioneering studies conducted by Wertheimer (1923) one can already venture the crucial importance of exploring interactions between different grouping factors. Wertheimer already designed patterns in which two grouping principles were combined. In particular, interactions between proximity and similarity cues were displayed in Figure 4.



A **B**

Figure 4. In matrix **A**, proximity and similarity cues add up to generate a stable organization. In matrix **B**, proximity and similarity cues compete for organizing discrete elements, giving rise to an unstable perception.

Some authors have argued that conjoined effects of grouping principles could be explained through an additive model. In this additive model, the final perception would be a product of the sum of the grouping strengths of each single principle (e.g., Kubovy & van den Berg, 2008).

1.3.1. Direct measures of perceptual grouping

As we have stated, when studying relationships between grouping factors, we must consider how strong they are individually. But how can we quantify the degree or strength of one grouping cue? Kubovy and van den Berg (2008) propose categorizing the quantitative methods that have explored the integration between grouping factors into two groups guided by different strategies: *the proximity-first strategy* and *the trade-off strategy*. The Proximity-first strategy proposes to measure first grouping by proximity and then measure other grouping factors, through its relationship with proximity cues. This strategy allows to measure which principle is more salient or strong, in addition to the degree of their salience. Similarly, this strategy also allows to build *grouping operating characteristics maps* (GOC) that include operations that reflect the interaction between several grouping factors. The Trade-off strategy is based on trade-offs between pairs of grouping cues. In this case, the grouping strength is determined through the combination of different principles acting simultaneously.

1.3.1.1. Proximity-first strategy

We will first summarize the results of those studies that used of *proximity-first strategy* to quantify grouping strength based on proximity cues.

Although Oyama (1961) did not investigate interactions between different grouping cues, it is important to mention his study as he developed a strategy to quantify proximity grouping strength on its own. He used rectangular 4x4 dot lattices in which distance along one orientation was constant but oscillated (in different trials) along the other dimension. Participants had 120 ms to observe these stimulus. Reaction times were recorded while participants manipulated distances in those axes between elements (competition between horizontal and vertical grouping organizations) by pressing one of the two buttons available during the task (Figure 5).

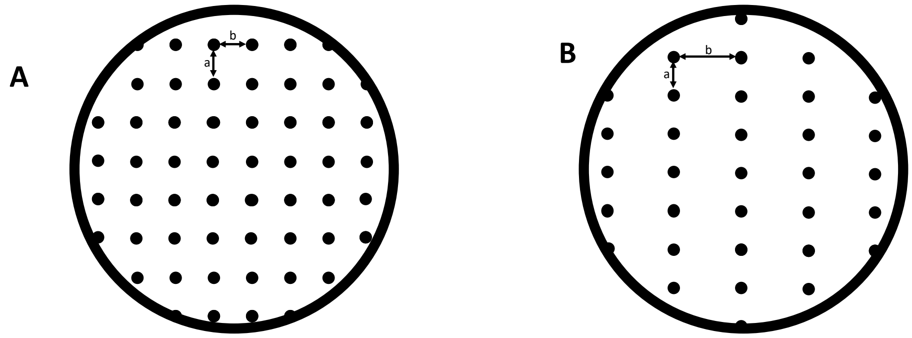


Figure 5. Example of dot lattices observed by participants in tasks such as the one designed by Oyama (1961). These matrices have been used in different studies devoted to quantify proximity grouping cues. **(A)** When distances between dots are equivalent in both rows and columns (between vectors *a* and *b*) the probability that participants perceive rows and columns is the same. **(B)** However, when distances are manipulated (*b*) changes in relation to the other (*a*), the strength of the shortest distance is predicted by a negative power function.

Oyama reported that the ratio of time that participants observed horizontal and vertical organizations could be represented as an exponential function of the proportion between vertical and horizontal distances. The drawback of its results is that only reported relative contributions of two of many possible organizations within the lattice in 2D dimension. Later, in the 90s, other studies found that grouping by proximity could be understood as an outcome of a probabilistic competition between potential perceptual organizations (Kubovy & Wagemans, 1995; Kubovy, Holcombe & Wagemans, 1998).

Distances between individual dots in two orientations of lattices were equal so, the chances of seeing one orientation or another were the same as well. If a distance in one orientation becomes larger than other, the relative chance or probability to perceive that orientation decreases. In these works (e.g., Kubovy & Wagemans, 1995; Kubovy, Holcombe, & Wagemans, 1998), they displayed different dot lattices in which lengths between *a* and *b* vectors were manipulated, and they also controlled the angle between them. Stimuli were displayed 300 ms and the task was to indicate the perceived orientation among four options. They estimated the probability of perceive one orientation or another, building a plot based on relative frequencies as a function of relative distance. They called that linear function *"attraction function"* whose slope is a measure of proximity sensitivity. This curve indicated that grouping by proximity relies on the relative distance between dots in situations in which several organizations competed, but not in overall configurations in which competition occurs. This finding is also named as *the pure distance law* and establishes how grouping operations varied as a function of relative distances, so perceptual grouping cues could be expressed as a collection of curves such as the one generated for proximity. In subsequent research, it has been suggested that other visual features, such as curvilinear structures, can play a fundamental role in grouping by proximity (Strother & Kubovy, 2006). Other studies have been reported similar effects (e.g., Claessens & Wagemans, 2008).

Kubovy and van den Berg (2008) examined interactions between proximity and similarity cues, again using rectangular dot lattices that varied in their contrast. Dots of the same contrast were arranged along the shorter axis (similarity and proximity in conjunction) or arranged along the larger axis (similarity versus proximity in competition). Dot lattices varied into two dimensions: the ratio between short and long axes of each rectangle of dots within the lattice and the contrast difference between arrays of dots (Figure 6).

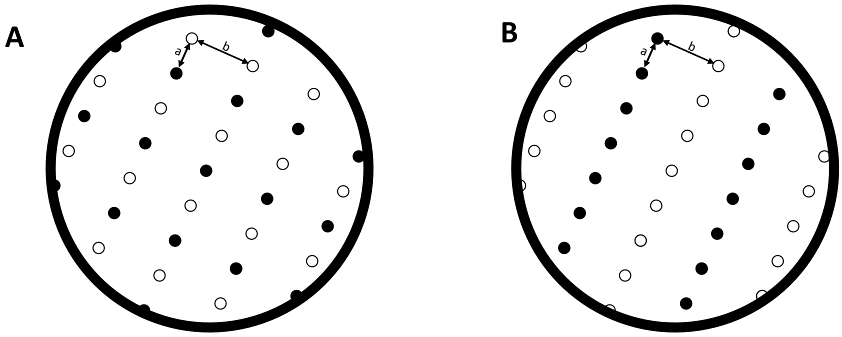


Figure 6. Examples of stimuli taken from Kubovy and van den Berg studies (2008). Dots with the same contrast were arranged along the longer axis (similarity versus proximity in competition) or arranged along the shorter axis of each rectangle of dots within the lattice (similarity and proximity in conjunction).

Participants had to identify which one of four possible orientations was the right one in each trial. Stimuli were presented for 300 ms. These authors built curves plotting the log likelihood of each reported orientations. The conjoint effects found between both grouping factors were reported as additives, as the curves obtained were parallel in log-odds space. These experiments have showed that it is possible to quantify certain effects of grouping based on proximity cues. It also underlines the importance of exploring additive effects between these multiple cues.

1.3.1.2. Trade-off strategy

A different set of studies relied on the *trade-off strategy* will be detailed below.

Rush's (1937) examined interactions between proximity and similarity cues in her pioneering research. In this experiment, participants observed sequences of dot lattices in which distances between these dots in one orientation remained constant, while distances between dots in the other orientation decreased from trial to trial. Observers reported the perceived orientation, choosing among five possible response options.
The results showed a competition effect between proximity and similarity cues. The conclusion reached by the author was that the grouping strength of these principles could be measured by finding the point of balance between the grouping strengths of each single grouping factor. In fact, she claimed that to match the grouping strength of both cues, similarity is equivalent to approximately 1.5 cm in proximity. Hochberg and Silverstein (1956) also examined interactions between proximity and luminance similarity using rectangular patterns composed by squares. The task consisted of adjust distances between squares in order to match the strength of luminance similarity features. These authors also tried to measure the strength of similarity grouping by making this principle to compete against proximity grouping. They manipulated luminance and distance features. Their results indicated a combination of additive effects between both principles, although these authors did not consider the relative strengths of each single principle. The relationships between proximity and similarity cues (similarity of colour and similarity of shape) were also explored by Quinlan and Wilton (1998). They designed a collection of stimuli that consisted of a row of seven geometric elements (squares or triangles) whose target was located in the central element. The task consisted of rating the degree to which a central target was grouped with the three elements located on its

left or its right (Figure 7). They used a numerical scale that allowed to rate grouping strength of different cues (subjective ratings). In their experiment, they manipulated three different conditions: *cooperation*, both grouping cues operate in the same direction to group elements; *competition*, each grouping cue operates by grouping elements in opposite directions; *grouping cues acting alone*, there is no interaction between both cues. Their results showed that even though proximity seemed to be dominant in the interaction, it could also be neutralized by similarity grouping cues.

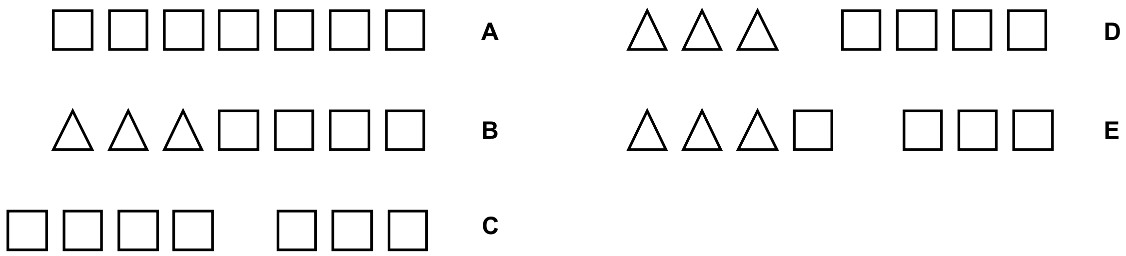


Figure 7. Examples of stimuli used in Quinlan and Wilton experiments (1998). **(A)** Pattern not grouped. **(B)** Grouping by shape similarity. **(C)** Grouping by proximity. **(D)** Cooperation between proximity and grouping by shape similarity cues. **(E)** Competition between proximity and shape similarity cues.

Kubovy and van den Berg (2008) conducted further analysis of data from Hochberg and Silverstein (1956) studies. They found an additive effects when proximity and similarity cues were combined in the same pattern. Similarly, they reanalysed data from Quinlan and Wilton (1998) studies. They observed again additive effects on the integration between grouping cues. However, their conclusions were limited as the experimental design did not include a measure of the degree of grouping strength, only the presence or absence of these principles. Luna and Montoro (2011) inspired by the

Quinlan and Wilton's (1998) experiment, examined interactions between proximity, luminance similarity and shape similarity cues, as well as, they included common region cues, a kind of extrinsic grouping cue. They examined cooperation and competition operations, as well as performance on each single cue. They obtained direct subjective ratings of grouping strength. Their results were compatible with an additive model of grouping effects. In the same way, their findings supported a strong consistency regarding intra-individual responses when participants responded to displays in which principles were acting alone and also in cooperative conditions. However, response consistency was moderate when common region and shape similarity competed and much lower when common region and proximity cues competed. Luna and Montoro (2011) suggested that these differences could be explained by the nature of each cue. The shape similarity principle is based on intrinsic relationships between its discrete element's features (colour, size or shape). In contrast, proximity and common region cues are based on spatial relationships: while proximity is based on distances between elements, common region is based on the interaction between discrete elements and an external element that induces them to group. Similarly, they suggested that both intrinsic and extrinsic principles make an independent contribution to perceptual organization when they are combined in the same visual pattern (see Montoro & Luna, 2015, for a similar account).

1.3.2. Indirect measures of perceptual grouping

The studies described above are based on subjective or phenomenological measures. Thus, aspects such as response accuracy or reaction times were not considered. In the same way, these studies used direct measures to study grouping operations, as in these tasks participants reported their phenomenological visual experiences.

A different set of studies developed more recently has collected quantifiable responses by means of indirect measures based on interference or facilitator effects of non-attended grouping configurations. Indirect methods arbitrarily define a correct response according to a specific organization of visual stimulus or pattern. Observers should deploy their attention to a particular configuration, while ignoring other grouping alternatives. It is suggested that participants could be aware of these grouping operations. Basically, participants are instructed to indicate whether a central element target is grouped to a cohort of elements located to its right or its left (e.g., Luna et al., 2016; Montoro et al., 2015). Alternatively, participants have to identify the perceived orientation of different dot arrays (e.g., Han 2004; Schmidt & Schmidt, 2013) based on an a priori defined grouping factor. Luna, Villalba-García, Montoro and Hinojosa (2016) examined dominance dynamics of perceptual grouping cues by means of a paradigm in which participants selectively attended to perceptual groups based on several grouping cues in different blocks of trials. These stimuli were inspired by prior investigations (Quinlan & Wilton, 1998; Luna & Montoro, 2011) where grouping strength was controlled (trade-off strategy). Reaction times and response accuracy were measured. They carried out three experiments: Experiment 1: proximity vs. shape similarity; Experiment 2: common region vs. connectedness; Experiment 3: shape similarity vs. common region (Figure 8).

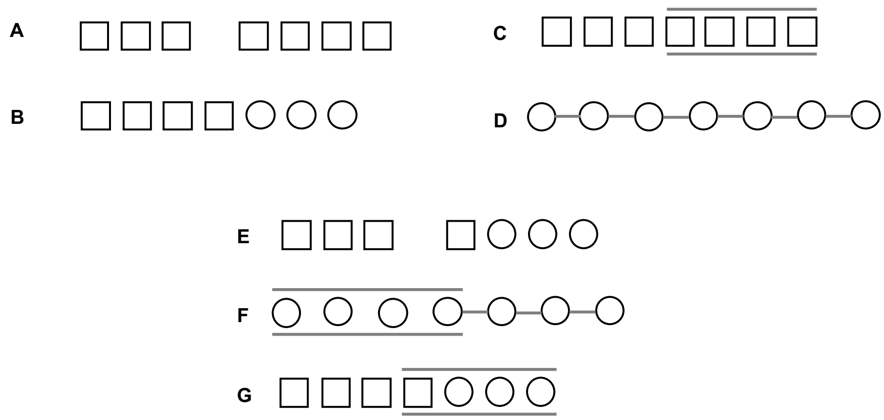


Figure 8. Examples of stimuli used by Luna et al. (2016). Experiment 1: **(A)** Single Proximity **(B)** Single shape similarity **(E)** Competition between proximity and shape similarity cues. Experiment 2: **(B)** Single common region **(C)** Single connectedness **(F)** Competition between common region and connectedness cues. Experiment 3: **(C)** Single common region **(D)** Single shape similarity **(G)** Competition between common region and shape similarity cues. The target was always the central element of a row of seven geometric figures that could be grouped with the three elements located on its right or with the three elements located on its left, only one answer was correct in each trial.

The authors found a dominance of common region cues over both connectedness and similarity cues. In contrast, no predominant factor was found in the integration between proximity and similarity cues. One of the most remarkable results of their work is that when two grouping cues compete, both the non-attended cue or non-dominant is still perceived and it is not completely lost.

As we already pointed out, methods based on directed attention can generate the use of alternative strategies, which might not be primarily related to perceptual grouping operations (Kubovy & Gepshtein, 2003). Therefore, other quantitative methods have been proposed, which are based on directing attention to aspects of the task other than grouping operations. As an example, Palmer and Beck (2007) developed the Repetition discrimination task (RDT) to measure perceptual grouping operations. The task consisted of searching two repeated adjacent elements (circles or squares) displayed in a row of seven geometric elements. Their design included a control condition, in which circles and squares were located equidistant from each other (neutral conditions), and two other conditions in which proximity cues were manipulating in order to hinder or improve the visual search task. In some trials the two repeated adjacent elements were within the same group (intra-group condition: two elements closer together, segregated from rest of elements) whereas in other trials, the two repeated adjacent elements were in different groups (inter-group condition: each repeated element was closer to other geometric element and segregated from the other repeated element) (Figure 9). Their results showed that repeated elements were identified faster in the intragroup condition than when target elements belonged to different groups. The authors found similar effects examining different perceptual grouping cues, such as similarity, colour, common region and connectedness cues (Palmer & Beck, 2007).

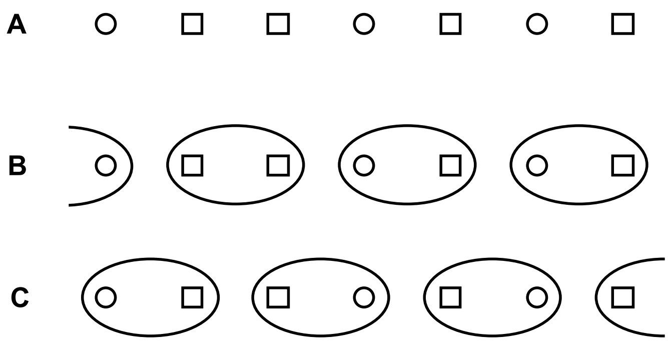


Figure 9. Examples of stimuli used by Palmer and Beck (2007). **(A)** No presence of grouping principle. **(B)** Principle of common region, target pair within group. **(C)** Principle of common region, target pair between groups.

Montoro et al. (2017) examined the competition between two extrinsic grouping cues (common region and connectedness) by means of an RDT (Palmer & Beck, 2007). Participants had to identify the repeated shape (square or circle) in a row of nine alternating elements. Common region or connectedness cues could facilitate or hinder their visual search. The novelty of this study lies in the inclusion of competition processes between two different grouping factors acting conjoined in the same pattern. As noted above, a critical aspect is to control the subjective saliency of each grouping factor (Schmidt & Schmidt, 2013). For this reason, in this study a scaling task was performed prior to the RDT to equate the grouping strength of both cues. In the scaling task participants had to equate the grouping strength of both principles by adjusting the thickness values of connectors (connectedness cues) while the ovals (common region cues) remained unaltered. Moreover, a customized value was obtained for each participant, which was used in the subsequent RDT. Despite these prior adjustments, a clear dominance of common region cues emerged. These results supports a dissociation between phenomenological judgements and visuomotor operations. The dominance of common region over other grouping factors has been reported by previous studies both using phenomenological measures (Luna & Montoro, 2011; Montoro & Luna, 2015) and objective measures (Montoro et al., 2015; Luna et al., 2016) and has even been corroborated in applied areas such as visual communication design (e.g., Bae & Watson, 2014).

As a conclusion about different measures of perceptual grouping, the combination of these multiple methods could be crucial to make an integrated characterization of these perceptual grouping operations.

1.4. Neural mechanisms of perceptual grouping

Palmer (2003) proposed four approaches related to these perceptual grouping operations: neural, structural, ecological, and computational (see also Prieto, 2018, for a similar account). Palmer established that these four approaches not only were not mutually exclusive, but also their relationships between these could give us an integrated vision of this phenomenon. As it was mention in more detail in previous sections, Gestalt psychologists focused on structural simplicity concept, and therefore, later researchers have continued research on the analysis of regularities of the pieces that compose the visual scene.

Gestalt psychologists already suggested that phenomenological experience would also be translated into brain operations, which would involve structures from retinal to cortex. In the words of Palmer (2003): *"These regularities simply are the particular kinds of stimulus structure to which the visual system is sensitive as a result of its underlying physiological mechanisms, whatever those might be."* (Palmer, 2003, p. 5). Although developments about neural correlates of grouping are relatively recent, Köhler (1938) already tried to formulate a theory about brain processes related to perception and he proposed an *electrical field theory* as an explanation of cortical integration in the human visual system.

Classical theories have assumed that perceptual grouping operations act early, practically preattentively, and always being a bottom-up process that contributes to later processes in which attention plays a crucial role (e.g., Anderson, 1997; Gilchrist et al., 1999; Julesz, 1975, 1981; Neisser, 1967). Nevertheless, previous studies carried out in the 60s (e.g., Rock & Brosgole, 1964) and in the 90s claim that grouping processes are not necessarily an early step in stages of visual processing (e.g., Palmer, 2003; Palmer & Rock, 1994a,b). In fact, it has been suggested that grouping processes may occur at many different levels or stages of processing (Palmer, Brooks, & Nelson, 2003) or that different grouping factors are related to different brain areas (e.g., Roelfsema, 2006). Several studies have suggested that different grouping processes may vary in their temporal course (e.g., Ben-Av & Sagi, 1995; Han & Humphreys, 1999; Kurylo, 1997). Perceptual grouping effects are also influenced by high-level visual processes (Murray, Schrater, & Kersten, 2004), such as perception of illusory figures, amodal completion, stereoscopic depth perception, shadow and transparency perception in lightness constancy. In the same way, these more complex processes influence perceptual organization mechanisms exerting top-down influence.

A set of studies has found differences regarding the temporal course of different grouping principles such as proximity or similarity cues (e.g., Han, 2004; Han, Ding, & Song, 2002; Han & Humphreys, 2007; Mao et al., 2004) and between other grouping cues such as collinearity and similarity (e.g., Casco, Campana, Han, & Guzzon, 2009). Many of these studies have recorded event-related potentials (ERPs) since they provide a powerful tool to explore the temporal dynamics of these grouping factors given the high temporal resolution of this technique (e.g., Razpurker-Apfeld & Pratt, 2008; Sasaki, 2007). However, as will be explained much more in depth in the following sections of this manuscript, despite found previous studies (e.g., Han, 2004) the lack of research devoted to explore correlates of interactions between multiple grouping principles (competition or cooperation relationships) is evident.

1.5. An ecological point of view

The ecological approach (Gibson, 1979) has also influenced the study of perceptual grouping. Ecological approaches suggest that the mechanisms underlying perceptual grouping operations are devoted to select parts of the image that correspond to the same object of the environment (Palmer, 2003). Organisms that are capable to extract and organise correctly visual information are more likely to survive than those that do not have this ability. But, how does our system know what information is relevant to construct our visual scene based on a sensory input? Perhaps it is a matter of evolution and natural selection, as Palmer (2003) suggests.

It should be noted that the extraction of these regularities could be also a consequence of learning during our childhood (Quinn & Bhatt, 2005). Briefly, some research suggests that infants are able to group visual elements into more complex structures. In fact, the ability of grouping by lightness similarity has already been observed in neonates (Bhatt & Quinn, 2011). Also, three-four months old infants organize elements based on good continuation, proximity, connectedness and common region cues (Gerhardstein, Kovacs, Ditre, & Feher, 2004). Other phenomena related to shape perception guided by similarity cues does not seem to be evident until after six or seven months of age (Quin & Batt, 2006). Similarly, several authors have stressed the importance of examining past experience influence exerts on perceptual grouping operations, which has been studied in adult population (e.g., Hadad & Kimchi, 2006; Kimchi & Hadad, 2002; Vickery & Jiang, 2009; Zemel et al., 2002).

Thus, it seems that our visual system is more sensitive to some sorts of organizations than others, which could be guided until some extent by survival and evolution. In nature, there are many examples, such as the ability to camouflage of some animal species (Palmer 1992). Similarly, some studies have suggested that we are sensitive to characteristics such as symmetry (Treder, 2010) as adults identify faster and more accurately response patterns with symmetrical stimuli.

1.6. Computational approach

Computational theories propose to decompose our visual scene in a set of parts that are assembled to give rise to images we perceive and therefore whose parts also interact with each other. David Marr (1977) already designed a computer program that applied the principles of perceptual grouping (such as proximity, similarity or good continuation). This program examined an input image and identified underlying perceptual structures. However, these images did not allow to extract regularities unless more information was provided to the program about what was being sought (our cognitive system is guided by selective attention operations). In fact, several studies have been devoted to propose different models that explain mechanisms underlying perceptual grouping operations (e.g., Ross, Grossberg, & Mingolla, 2000). Subsequent research has tried to model proximity and good continuation principles using 3D histograms, applying nonparametric statistical approaches (Geisler et al., 2001). The goal of these models is to combine different laws in an optimal way and study their interactions. Elder and Goldberg (2002) concluded that good continuation, similarity and proximity cues statistics were not correlated. Interestingly, they found that the most powerful principle was proximity, as it reduced entropy by almost 75% while principles as similarity and good continuation contributed to reduce entropy by 10% respectively. According to their probabilistic model, the most optimal visual decision would be to combine the effects of all these cues, which would be closer to the interpretation we get of natural images

Prägnanz principle, as discussed at the beginning of this introduction, has always been accused of being vaguely defined by Gestalt psychologist. However, its basic idea is similar to those proposed by Bayesian inference. The Bayesian approach suggests that our system selects the most optimal environment organization based on the elements that constitute and build the visual scene. One of the current challenges in this area is to model probability curves for objects and scenes. Bayesian inference lets quantify the degree to which different scenes models (the range of hypotheses about what is happening in visual scenes) must be believed based on sensory data (Feldman, 2014). Grouping operations can be understood as the estimation of a number of parameters of mixture components that generated the image, including estimating which image elements are "owned" by which objects (Froyen, Feldman, & Singh, 2015). This approach unifies top-down attention and bottom-up perceptual inference in a hierarchical system. Attention is considered a collection of top-down priors, due to its influence in perceptual inference at earlier levels of visual processing (e.g., Lee, 2003). The recurrent feedback provided by context and attentional priors gives us a more sophisticated view of the nature of cortical computations related to perceptual organization. It is a suitable approach to study perceptual grouping operations as it is based on estimating properties of our physical world based on primarily sense data provided by our sensory system.

Some classical laws have been studied in this context, such as proximity or good continuation cues (see Wagemans et al., 2012a, for a review). It should also be noted that a fundamental problem again is the lack of definition of these Gestalt cues, which hinders translating these laws into computational designs. Bayesian inference could provide a complementary mathematical framework regarding perceptual grouping operations.

2. Research objectives

The present doctoral thesis aims to study cognitive and neural mechanisms underlying perceptual groping operations in visual modality.

As a first goal, in **Experimental Study I** dominance dynamics between two Gestalt classic grouping cues such as proximity and shape similarity have been examined by means of a selective attention paradigm. This method allows measuring independently the contribution of each cue to the competition between them. Also, we explored the temporal course of these perceptual grouping operations through the use of an electrophysiological technique (ERPs) to identify possible neural markers involve in the integration between these cues. It should be noted that classic rules on dominance (Navon, 1977, 1981; Ward, 1983) have been assumed to examine the integration between multiple grouping factors in this study. Specific, one grouping cue will dominate perceptual organization over other grouping cues when: (a) it generates faster and/or more precise responses; (b) it is less interfered by another grouping cue in competition; (c) in cooperation, its contribution leads to a more stable perception, improving reaction times and response accuracy. Just to be clear, in this manuscript no cooperative relationships between perceptual grouping principles will be explored.

Second, the competition between several grouping principles has been examined in **Experimental Study II**. For that, we used an indirect task (i.e. repetition discrimination task, RDT) without explicit attention to grouping factors to further examine the rules that govern dominance between competing grouping principles. Our study inquired about possible dissociations between direct phenomenological and indirect objective reports of grouping strength. Therefore, for the first time, we designed an *objective equating task* to try to ensure that grouping strength mediated by the visuomotor system was matched between cues prior to RDT, complementary to participants' subjective ratings. In **Experiment 1**, the competition between proximity and luminance similarity cues have been examined. In **Experiment 2**, the competition between common region and connectedness cues have been explored. Additionally, a more exhaustive analysis of individual data has been carried out.

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3. Experimental Study I

Villalba-García, C., Santaniello, G., Luna, D., Montoro, P. R., & Hinojosa, J. A. (2018). Temporal brain dynamics of the competition between proximity and shape similarity grouping cues in vision. *Neuropsychologia*, *121*, 88-97.

Abstract

Perceptual grouping operations are crucial for visual object recognition. From the pioneering proposal of Gestalt psychologists, research has focused mostly on the dynamics of single grouping laws. However, the integration between grouping cues has received relatively less attention. The present event-related potentials (ERPs) study aimed to examine the brain correlates of the competition between multiple grouping cues (namely, shape similarity versus proximity) in visual patterns by means of a selective attention paradigm that allows to measure the contribution of each cue independently to the competition between them. Behavioural results indicated larger interference effects of shape similarity on proximity cues when both cues compete. ERPs data showed two main neural effects. First, the amplitude of a negative component peaking around 250 ms (N200) was modulated by the interaction between proximity and shape similarity cues. Specifically, the single shape similarity relative to competing shape similarity cues elicited enhanced amplitudes. This finding seems to reflect the visual salience and/or the processing fluency of the shape similarity grouping factor. Remarkably, it can be considered an indirect brain signature of the competitive interaction between grouping cues. Second, we found larger P300 amplitudes elicited by single displays compared with competing trials, as well as by proximity relative to shape similarity cues, which presumably reflects higher perceived confidence in decisions during the processes joining perception to action.

Keywords: Proximity; Shape Similarity; Gestalt; Intrinsic principles; Competition; Event - Related Potentials (ERPs).

3.1. Introduction

The principles of perceptual organization describe the mechanisms applied by the visual system to extract the regularities that are present in our environment in order to achieve meaningful representations of the world. In a first formulation, Wertheimer (1923) described five principles: proximity, similarity, good continuation, closure, and common fate. Within the last years, new principles of grouping have been described (see Brooks, 2015, for a review). Additionally, Palmer (1999) proposed a reclassification of grouping cues in two different clusters: intrinsic cues, based on inherent relationships between the properties of the grouped elements (like size, colour, position, etc.) and extrinsic principles, which require external elements to induce grouping (e.g., common region or connectedness).

An important theoretical -and practical- issue that is receiving increased attention is the study of the integration between different perceptual grouping factors to predict how single cues interact when they are conjoined in the same pattern. Originally, the grouping principles was formulated by the Gestalt psychologists as *ceteris paribus rules,* so that they only can predict the perceptual output when *other things remain equal* (Palmer, 1999). However, since natural images often contain many cues operating simultaneously, it is necessary to determine the rules governing the combination of different principles of perceptual grouping by means of experimental approaches. Although the majority of studies have explored the relationships between intrinsic principles like proximity, similarity or others (Ben-Av & Sagi, 1995; Claessens & Wagemans, 2005, 2008; Kubovy & van den Berg, 2008; Oyama & Miyano, 2008; Quinlan & Wilton, 1998; Schmidt & Schmidt, 2013; see Peterson & Kimchi, 2013, for a review), a few recent studies have examined extrinsic principles (Luna & Montoro, 2011; Luna, Villalba-García, Montoro

& Hinojosa, 2016; Montoro & Luna, 2015; Montoro, Villalba-García, Luna & Hinojosa, 2017). The study of the interaction between grouping principles becomes especially relevant if we consider that human beings must deal with challenging real environments that typically involve the simultaneous operation of different grouping factors.

Prior studies have investigated competing grouping principles with the aim of identifying the conditions that determine the dominance of a perceptual organization over the other (Palmer, 2000, 2007; Quinlan & Wilton, 1998; Kubovy & Van den Berg, 2008; Luna & Montoro, 2011; Luna et al., 2016; Montoro & Luna, 2014; Rashal et al., 2017; Schmidt & Schmidt, 2013;). Overall, evidence indicates stronger grouping effects when two cues cooperate and weaker effects when they compete, compared to grouping effects found for each single principle. Interestingly, there is also evidence suggesting that when two grouping cues compete, the non-attended or non-dominant cue is perceived to some extend (Luna et al., 2016; Rashal et al., 2017).

Behavioural studies using phenomenological measures have reported weaker grouping effects when proximity and similarity cues compete relative to grouping effects found for each single principle. In contrast, the cooperation of these principles enhances grouping effects (e.g., Quinlan & Wilton, 1998; Luna & Montoro, 2011). In these tasks, it is noteworthy that participants provide subjective ratings of the grouping strength for each trial, so their assessments could rely on cognitive rather than perceptual judgements. A different approach has been to examine speeded visuomotor processing of grouping cues during the competition between intrinsic grouping principles. In the study by Schmidt and Schmidt (2013), the authors matched grouping strength and still found differences in the processing of the distinct grouping cues. Thus, it seems that subjectively equating two stimuli does not guarantee similar effects in the visuomotor system. These authors concluded that their data reflect dissociation between direct and indirect measures. In this sense, perceptual parameters determining grouping strength would not be necessarily represented in the same manner by the phenomenological perception and the visuomotor system. Interestingly, some authors have argued that none of these measures predominates over the other and both could be convergent measures of perceptual grouping (Kubovy & Gepstein, 2003; Palmer & Beck, 2007). Therefore, it seems crucial to characterize and integrate measures from different perspectives.

The high temporal resolution of event-related potentials (ERPs) makes this technique suitable to track the temporal dynamics involved in the processing of grouping principles (Razpurker-Apfeld & Pratt, 2008). Prior evidence from ERP studies has shown differences in the time-course of the processing of proximity and similarity cues (e.g., Han, 2004; Han, Ding & Song, 2002; Han & Humphreys, 2007; Mao et al., 2004). In this line, proximity relative to shape similarity grouping cues have been consistently associated with enhanced positive amplitudes around 100 ms over occipital electrodes (P100), which has been interpreted to reflect an early representation of spatial relationships between local elements (Han, Ding, & Song, 2002; Han, Song, Ding, Yund & Woods, 2001; Han, Jiang, Mao, Humphreys & Qin, 2005b). Additionally, larger amplitudes in central and parietal electrodes around 300 ms (P300) have been observed for proximity when compared to similarity conditions. These effects seem to indicate differences in confidence for perceptual decisions (Han et al., 2001). In contrast, grouping by similarity relative to proximity has been associated with increased amplitudes in an occipito-temporal negative component (N200) peaking between 240 and 340 ms. These effects are thought to stem from attentional post-perceptual operations related to the discrimination and selection of stimuli features needed to complete shape identification based on low-level factors (e.g., collinearity) (Han et al., 2001, 2002, 2005a, 2005b).

Surprisingly, to our knowledge, only one previous study has directly examined the brain correlates of the competition between Gestalt grouping cues. In an ERP study, Han (2004) displayed stimulus arrays in which local circles and squares were grouped into rows or columns based on either proximity or similarity. Half of these arrays included proximity and similarity cues that were congruent in grouping local elements, whereas these two cues were incongruous in the other half of the stimulus arrays. The participants' task was to identify the orientation of these perceptual groups. An interaction between both grouping cues was found between 180 ms and 220 ms over posterior temporal-parietal areas. Larger negative amplitudes were observed for similarity-grouping cues in the congruent compared to the incongruent proximity cue condition. Remarkably, since the processing of proximity cues was not modulated by congruency with similarity cues within this latency, the authors concluded that proximity grouping-processes interfered with the processing of shape similarity grouping. Additionally, proximity relative to similarity grouping elicited enhanced amplitudes for the P100 and P300 components, although these effects were not modulated by congruency. Interestingly, in the study by Han (2004), congruent arrays included two single cues combined in cooperation, thus, it was not possible to examine the contribution of single grouping cues to the competition between proximity and similarity grouping. To overcome this limitation, in the current study, we have recorded ERPs to explore the temporal dynamics of the dominance of single and competing proximity and shape similarity cues. To this aim, we have used a grouping task recently introduced by Luna et al. (2016). This new grouping paradigm is inspired by research on dominance processing in hierarchical stimuli (e.g., Navon, 1981; Ward, 1983) and enables the examination of the contribution of single grouping cues to the interactions between grouping principles when they compete. The participants' task was to indicate the position in the display (left or right) of groups based on two different cues by selectively attending to one of the two perceptual groups while ignoring the alternative organization based on another cue. In two different blocks, participants were instructed to attend to one of the two grouping cues (proximity or shape similarity) while ignoring the other. Remarkably, this task allows testing the dominance of grouping cues by examining the relative advantage of single cues and the interference effects between competing cues. It can also be used to determine whether performance on competing cues could be predicted by performance on single cues (Luna et al., 2016). Considering all these characteristics, Luna et al.'s grouping task provides us with a useful experimental tool to explore the temporal brain dynamics of the competition between grouping cues, as well as the contribution of each single grouping factor to the integration between Gestalt principles. Based on prior reports showing modulation of the amplitude of a negative ERP component between 180 and 220 ms in posterior electrodes (Han, 2004), we expect modulations within this time window under conditions of competition between proximity and shape similarity grouping. Specifically, Han (2004) found that the amplitude of this component in the shape similarity grouping condition was larger for congruent relative to incongruent trials while its amplitude in the proximity grouping condition was not influenced by the congruency with shape similarity cues (Han, 2004). Based on this finding, we hypothesize enhanced amplitude of this negative component in the single shape similarity condition compared to the competing similarity condition, which would provide a brain index of the interaction between Gestalt grouping cues. We also hypothesize effects on the P100 and the P300 components elicited by single proximity cues (Han et al., 2001). At a behavioural level, in the current study, we expect to replicate prior results (Luna et al., 2016). In particular, single displays should be responded faster and more accurately in comparison to combined displays.

In sum, the integration between grouping cues is a crucial question in vision science and the application of high-temporal resolution methods such as ERPs is especially advisable to explore the temporal dynamics of the neural correlates underlying the interaction between Gestalt principles. The present study aims to characterize the brain correlates of the competition between two classical grouping factors (i.e. proximity and similarity) by means of a paradigm designed to dissociate the single contribution of each grouping cue and to measure the interference effect of the competing principles.

3.2. Material and methods

3.2.1. Participants

Twenty-four students (12 females and 12 males) from the Universidad Complutense de Madrid participated in the study for course credits. The age range was between 18 and 32 years (mean=20, 25, SD= 3, 06). Written informed consent (see Appendix III) was obtained from each participant, and all of them reported normal or corrected-to-normal vision. The research was conducted in accordance with ethical guidelines of the local committee and conformed to the Declaration of Helsinki.

3.2.2. Stimuli and apparatus

To make sure that the grouping strength of both cues was similar, we used stimuli from Luna and Montoro's (2011) study ensuring that the visual angle and the luminance value of the stimuli was equal to those of the that work. The stimuli display consisted of seven elements arranged in a row. In the single conditions, the seven elements were organized into two cohorts by means of a single grouping cue (proximity or shape similarity): (1) four elements including the central element on one side (left or right) and (2) the other three elements on the other side. In the competing conditions, the central element could either be grouped by proximity or by shape similarity indistinctly. Thus, if the central element was grouped by proximity with the elements on one side of the display (left or right), then this central element was grouped by shape similarity with the elements on the alternative side, in order to get a competition between grouped percepts (Fig. 1). The shapes used were squares (11 mm × 11 mm) and circles (11 mm in diameter) which subtended 1.0° at a viewing distance of 60 cm. The regular distance between the elements was 3 mm (0.3°). In stimuli displaying proximity cues, the distance between the target element and one of the flanker cohorts of elements was 9.5 mm (0.9°). The shapes were made of black lines (0 RGB) and presented on a white background (255 RGB).

Six different stimulus arrays were constructed entangling grouping cues as well as their mirror images for a total of twelve stimuli, divided into two sorts of displays: single or combined in competition cues. In single displays, the central element could be grouped with the elements on the left or on the right, based on only one grouping cue (for example, grouping by proximity). In combined displays, the two grouping cues always competed. Thus, the central element could be grouped with the elements on one side of the display if grouping was based on shape similarity and on the other side if it was based on proximity.

In each block, there were a total of eight different stimuli taken from the whole set of twelve experimental stimuli. In shape similarity-directed blocks, there were two shape-only displays (and their mirror images) and two conjoined competing displays (and their mirror images). In proximity-directed blocks, there were two proximity-only displays (and their mirror images) and two conjoined competing displays (and their mirror images) (Fig. 1).

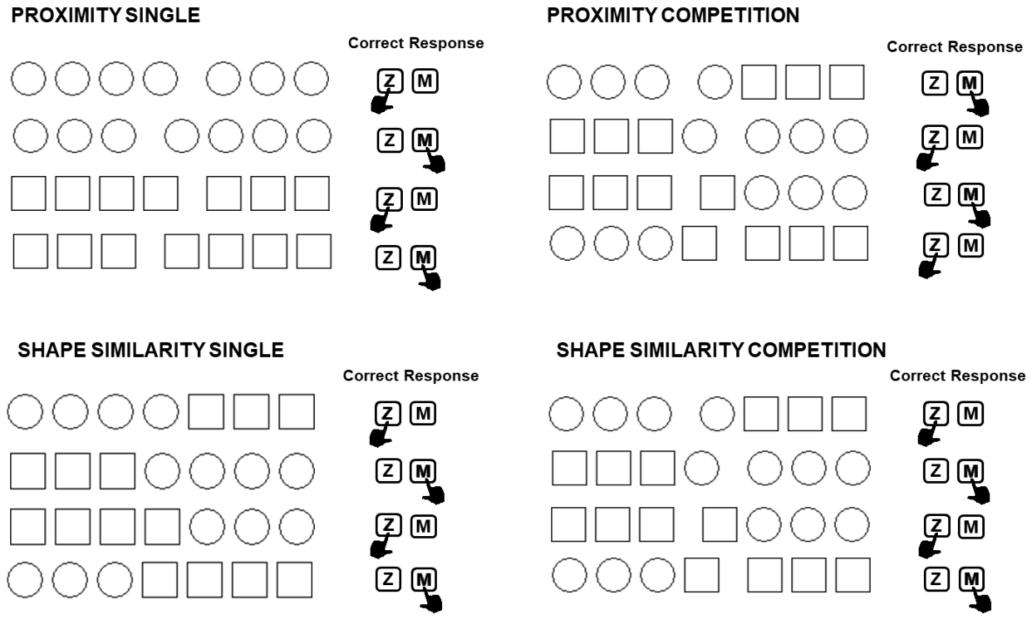


Figure 1. Experimental stimuli and correct responses depending on the experimental block. Each row of seven elements represents a stimulus. The correct response for each trial is indicated by a hand pressing the correct key. The "Z" key indicates the grouping of the central element with the three elements located on the left. The "M" key indicates the grouping of the central element with the three elements located on the right. In proximity single and proximity competition conditions, participants had to attend exclusively to the cohort grouped by proximity and to ignore the shape similarity cue. In shape similarity single and shape similarity competition conditions, participants had to attend to the cohort grouped by shaped similarity while ignoring proximity factor.

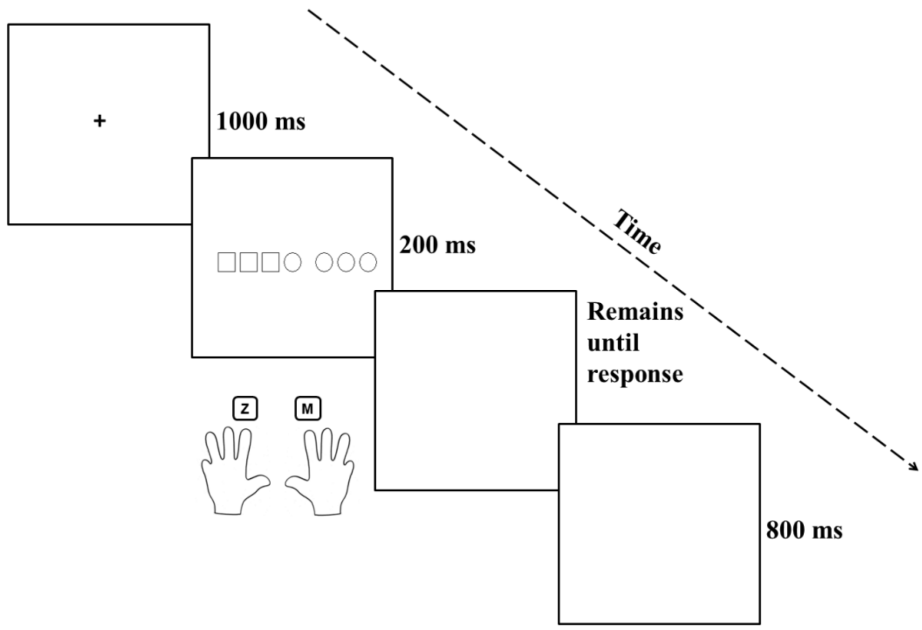
The stimuli were presented on a 19-in. LCD-LED Samsung 943 N colour monitor with a 75-Hz refresh rate, a 5:4 aspect ratio, and a resolution of 1024 x 768 controlled by a personal computer running E- Prime 2.0 Professional software (Psychology Software Tools, 1996-2002). Viewing distance was approximately 60 cm.

3.2.3. Design and procedure

The 2 x 2 design included two within-subject factors: Stimulus type (single or combined grouping cues) and Directed attention (attention directed to groups based on proximity or on shape similarity grouping cue). RTs and error rates were taken as dependent variables.

Participants were tested individually in a quiet room. First, the EEG technique was briefly introduced to the participant and informed consent was obtained. Thereafter, electrodes for EEG acquisition were placed on the participant's scalp and we provided the instructions (see Appendix I). Examples of experimental stimuli were shown in the screen. In different blocks of trials, participants had to selectively attend to groups based on one of the grouping cues whilst ignoring the other, and to indicate whether the central element was grouped with the left or right elements on the basis of the attended/directed grouping cue. For example, in proximity directed blocks of trials, subjects were instructed to attend exclusively to groups based on proximity and ignore those based on shape similarity indicating whether the central element was grouped by proximity with the left or the right elements. On the other hand, in shape similarity-directed blocks of trials, they were instructed to attend to groups based on shape similarity and ignore those based on proximity. Each trial started with a cross-shape fixation mark at the centre of the screen; 1000 ms later, a stimulus was displayed at fixation for 200 ms and replaced by a blank screen that remained until response. There was an intertrial pause of 800 ms. There were two practice blocks (one for each attention condition: groups based on proximity or on shape similarity) and six experimental blocks (three for each attention condition). The selection of stimuli was randomized within blocks. The order of application of the blocks was counterbalanced across subjects. Each experimental block consisted of 80 trials, whereas each practice block consisted of 48 trials. There were 480 experimental trials in total, 120 trials for each condition. Feedback was provided only in the practice trials. The task of the participants was to indicate the position (left or right) of the cohort of elements grouped by the attended grouping cue (either shape similarity or proximity) by pressing the left (“Z”) or right (“M”) keys from the keyboard, making use of the index fingers of both hands (left index finger for “Z” key and right index finger for “M” key) (Fig. 2).

Figure 2. Timing and sequence of events of an experimental trial. In a shape similarity-



directed block, the correct response to this stimulus was the “M” key pressed by the right index finger. Alternatively, in a proximity-directed block, the correct response was the “Z” key pressed by the left index finger.

3.2.4. Recording and pre-processing

Electroencephalogram (EEG) activity was recorded through an ElectroCap cap with Ag/AgCl electrodes placed at 60 scalp sites distributed homogeneously over the entire scalp according to the 10-20 system (American Electroencephalographic Society, 1994). Electrodes were referenced to the linked mastoids. The electrooculographic activity was recorded using vertical and horizontal bipolar electrodes placed at supra-infraorbital level of the left eye and on the outer canthus of both eyes, respectively. The EEG and EOG were kept below 10kΩ. Recordings were amplified using BrainAmps amplifier, continuously digitized at sample rate of 1 kHz and filtered online with a frequency band-pass of 0.1–100Hz.

Analyses were conducted offline with software packages EEGLAB v.12.01 toolbox (Delorme and Makeig, 2004) implemented in MATLAB (Mathworks, Inc.). Recordings were down-sampled to 500Hz and filtered between 0.3 and 30Hz, using a basic FIR filter (12dB/oct. roll-off). Epochs were created with duration of 1000 ms (starting 200 ms before stimulus onset and ending 800 ms after stimulus onset). Baseline correction was applied on the post-stimulus interval using the 200 ms period prior to the onset of each trial. Only correct response epochs were further analysed. Prior to artefact correction procedures, epochs in which recordings at any channel exceeded ±150 µV were automatically discarded. An independent components analysis (Makeig et al., 1997) was performed to eliminate the blinks (Jung et al., 2000). Finally, epochs contaminated with gross artefacts were rejected after visual inspection.

This procedure led to average admission of 82.91% (11.3) in proximity single trials, 82.21% (8.11) in proximity combined trials, 80.05% (9.72) in shape similarity single trials and 81.41% (12.22) in shape similarity combined trials. Grand averages waveforms were computed for each subject, experimental condition and electrode location.

3.2.5. Data analysis

3.2.5.1. Behavioural analysis.

Data on RTs and error rates were subjected to separate analyses of variance (ANOVAs) involving two factors Stimulus type (two levels: single or combined grouping cues) and Directed attention (two levels: to proximity or to shape similarity). Post hoc analyses were further performed with the significant level adjusted by the Bonferroni method. Effect sizes were computed using the partial eta-square (η_p^2) method. For the RT analysis, responses faster than 200 ms (anticipations) and slower than 1500 ms were excluded from the analysis as outliers (0.25% of total trials). Also, inaccurate responses were excluded (on average 3.92 %). All statistical analyses on behavioural and ERP data were carried out using IBM SPSS Statistics (version 20).

3.2.5.2. ERP analysis.

Detection and quantification of ERP components that have been previously related to the processing of single cues (P100 and P300) and the competition between proximity and similarity grouping cues (N200) was carried out through a temporo-spatial principal component analysis (PCA). The PCA has proven to be a reliable data-driven method to isolate the components shaping an ERP waveform (Chapman & McCrary, 1995; Dien, Beal, & Berg, 2005). The theoretical assumption underlying this method is based on the fact that values from time-points forming a component tend to vary in unison, whereas those that are part of the noise present a low covariance and mutually cancel themselves since they behave randomly. Among PCA outputs, factor scores are especially relevant since they are linearly related to amplitudes and may be submitted to statistical contrasts.

First, a covariance-matrix-based temporal PCA (tPCA) was used to disentangle ERP components over time. The main advantage of tPCA over conventional procedures based on a visual inspection of the recordings and on 'temporal windows of interest' is that it presents each ERP component separately and with its 'clean' shape, extracting and quantifying it free of the influences of adjacent or subjacent components. Indeed, the waveform recorded at a site on the head over a period of several hundreds of milliseconds represents a complex superposition of different overlapping electrical potentials. Such recordings can make ambiguous the interpretation of visual inspection. In brief, tPCA computes the covariance between all ERP time points, which tends to be high between the time points involved in the same component, and low between those belonging to different components. The solution is, therefore, a set of factors made up of highly covarying time points, which ideally correspond to ERP components. A temporal factor score, the tPCA-derived parameter in which extracted temporal factors may be quantified, is linearly related to amplitude (Carretié et al., 2004; Dien 2010). The Promax rotation system was used (Dien, 2010) and factors were rotated with a maximum of 100 iterations for convergence. The decision about the number of components to retain was based on parallel analyses. As we will explain later, the ERP components associated with single grouping cues processing (P100 and P300) and the competition between proximity and similarity grouping cues (N200) was satisfactorily identified and disentangled from other components.

Once quantified in the temporal domain, temporal factor scores were submitted to spatial PCA (sPCA) to decompose the scalp topography of those components linked to the processing of single and competing groping cues. Whereas tPCA separates ERP components along time, sPCA distinguishes ERP components along space, each spatial factor ideally reflecting one of the concurrent neural processes underlying each temporal factor. This spatial decomposition is an advisable strategy prior to statistical contrast, because ERP components frequently behave differently in some scalp areas than they do in others (e.g., they present opposite polarity or react differently to experimental manipulations). Basically, each region or spatial factor is formed with the scalp points where recordings tend to covary. As a result, the shape of the sPCA-configured regions is functionally based, and scarcely resembles the shape of the geometrically configured regions defined by traditional procedures. Moreover, each spatial factor can also be quantified through the spatial factor score, a single parameter that reflects the amplitude of the whole spatial factor. Retained factors were also submitted to Promax rotation.

Finally, spatial factor scores (equivalent to traditional amplitudes, as aforementioned) were analysed with repeated measures ANOVAs with the two-level factors Stimulus type (single or combined grouping cues) and Directed attention (attention directed to groups based on proximity or on shape similarity grouping cue). The Greenhouse-Geisser (GG) epsilon correction was applied to adjust the degrees of freedom of the F-ratios. Bonferroni- adjusted post-hoc tests were used to further analyse significant main effects. Effect sizes were estimated using the partial eta-square ($\eta_p 2$) method. The IBM SPSS Statistic (v.20) was the software used to carry out the analyses.

3.3. Results

3.3.1. Behavioural data

Mean RTs and mean accuracy (error rates) are shown in Table 1 and Figure 3. Analyses on RTs revealed a significant main effect of Stimulus Type F (1, 23) = 55.33, MSe = 37617.2, $p < 0.001$, $\eta_p^2 = 0.71$. A significant interaction effect between Stimulus Type and Directed Attention, F (1, 23) = 7.91, MSe = 14683.4, $p = 0.01$, $\eta_p^2 = 0.26$, was also observed. The main effect of Stimulus type indicated that RTs for single trials (491 ms) were shorter than those for competing ones (530 ms). The significant interaction between Directed attention and Stimulus type indicated that the interference effect of shape similarity on proximity cues (the difference between RTs to single and to combined displays) was greater (Δ65 ms, $p < 0.01$) than the interference of proximity cues over shape similarity (Δ15 ms, $p < 0.05$). Post-hoc comparisons between Stimulus Type and Directed Attention, reported significant differences between proximity single cues (476 ms) and shape similarity single cues (505 ms; $p < 0.05$), showing an advantage effect of proximity: RTs for single proximity cue were shorter than those for single shape similarity cue. In contrast, the comparison between both proximity (541 ms) and shape similarity (520 ms) competing conditions did not reach statistical significance ($p > 0.10$).

Individual hit rates ranged between 90% and 100%. The ANOVA on accuracy data showed a significant main effect of Stimulus type, F (1, 23) = 24.84, MSe = 0.046, $p <$ 0.001, $\eta_p^2 = 0.52$, indicating that participants were more accurate when the stimulus was presented single (hits: 98%) rather than in competition (hits: 93%) (both $ps < 0.001$). The analyses also reported a significant interaction between Stimulus type and Directed attention, F (1, 23) = 15.03, MSe = 0.006, $p = 0.001$, $\eta_p^2 = 0.40$. This interactive effect showed that the interference of shape similarity on proximity cues (the difference between errors for single and for combined displays) was greater ($p < 0.001$) than the interference of proximity cues over shape similarity ($p < 0.001$). Pair-wise comparisons with the Bonferroni correction found significant differences between all experimental conditions (all *ps* < 0.05). Remarkably, these results mirrored those obtained with RTs. There was no indication of speed–accuracy trade-off.

Table 1. Mean reaction time (ms), mean accuracy (hit rate) and standard errors (in brackets), interference (Interf.) and advantage indices for each condition.

	Stimulus Type					
	Reaction Time			Accuracy		
Directed Attention	Single	Comp.	Interf.	Single	Comp.	Interf.
Proximity	476 (73.7)	541 (120.8)	65	0.98 (0.13)	0.92 (0.27)	-0.06
Shape similarity	505 (75)	520 (68.3)	15	0.97 (0.17)	0.94 (0.23)	-0.03
Advantage	29	-21		-0.01	0.02	

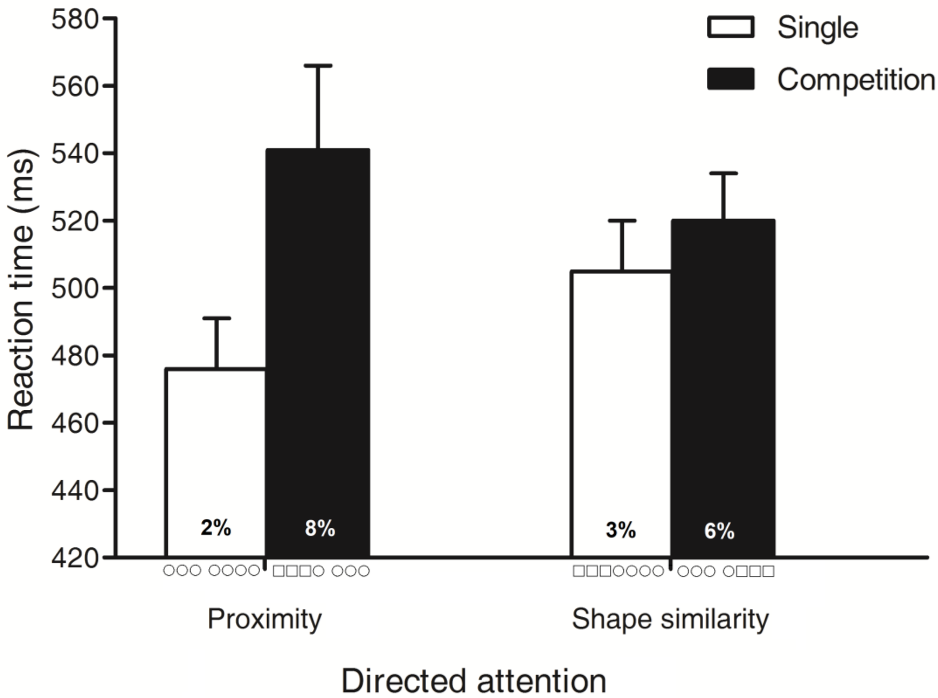


Figure 3. Mean reaction times (ms), standard error bars and error rates (percentages) for Directed attention (proximity vs. shape similarity) and Stimulus type conditions (single vs. competition).

3.3.2. ERP data

Figures 4 and 5 show a selection of grand averages in parietal and occipital scalp electrodes where effects were observed. These grand averages correspond to parieto-occipital (Fig. 4) and centro-parietal (Fig. 5) electrodes, where the critical experimental effects were more evident. As we described in the introduction, the processing of single grouping cues has been associated with positive ERP activity at posterior electrodes peaking around 100 ms (P100) and 300 ms (P300), whereas the competition between grouping cues have elicited modulations in a negative component at posterior electrodes around 200 ms. After applying the tPCA, 7 temporal factors were extracted from the ERPs. Figure 6 shows the factor loadings corresponding to these temporal factors. The time course and peak latency of TF4 (peaking at 100 ms), TF3 (peaking at 250 ms) and

TF2 (peaking at 380 ms) clearly associate these TFs to the P100, N200 and P300 components, respectively (Fig. 4 and 5). Once the main ERP components of interest to test the hypotheses of the current study with a data-driven procedure were identified, further sPCAs were only performed for these effects, i.e.: TF4 (P100), TF3 (N200) and TF2 (P300). This procedure allowed us to examine the topographical distribution of the significant differences between conditions.

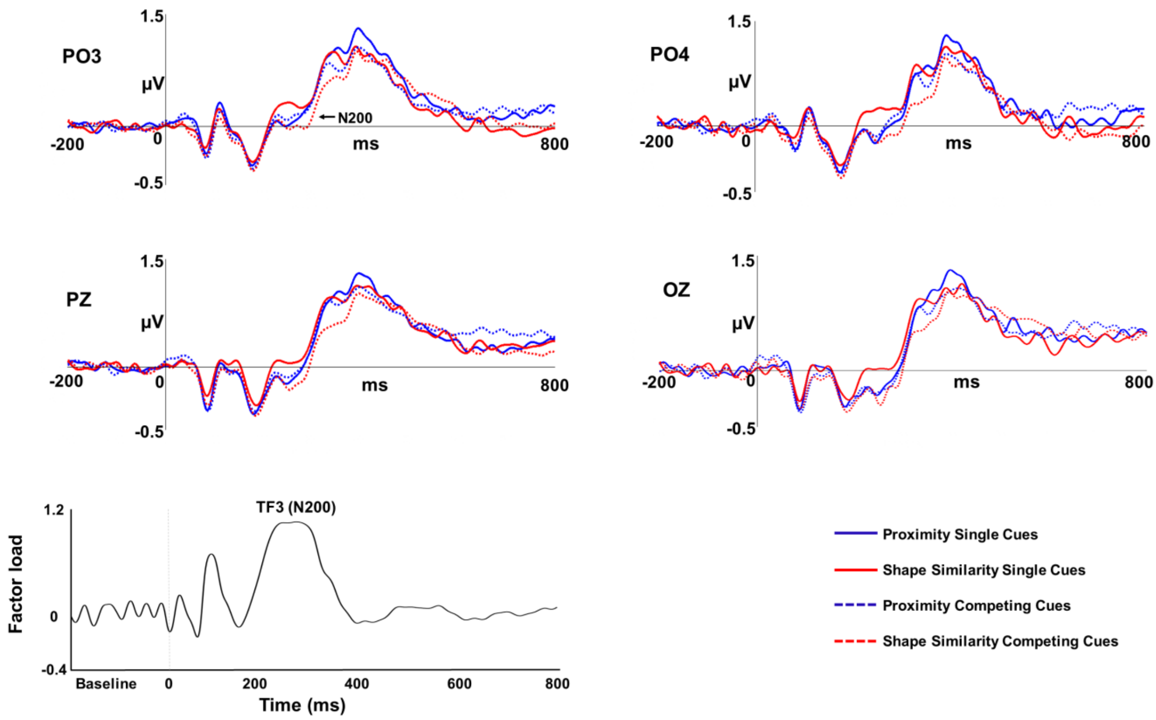


Figure 4. Top: Grand averages at parietal and occipital sites, where the experimental N200 effects described in the text are visible. Bottom: Factor load after promax rotation, temporal course and peak latency of the TF3(N200), which was extracted from the temporal principal component analysis. TF: temporal factor.

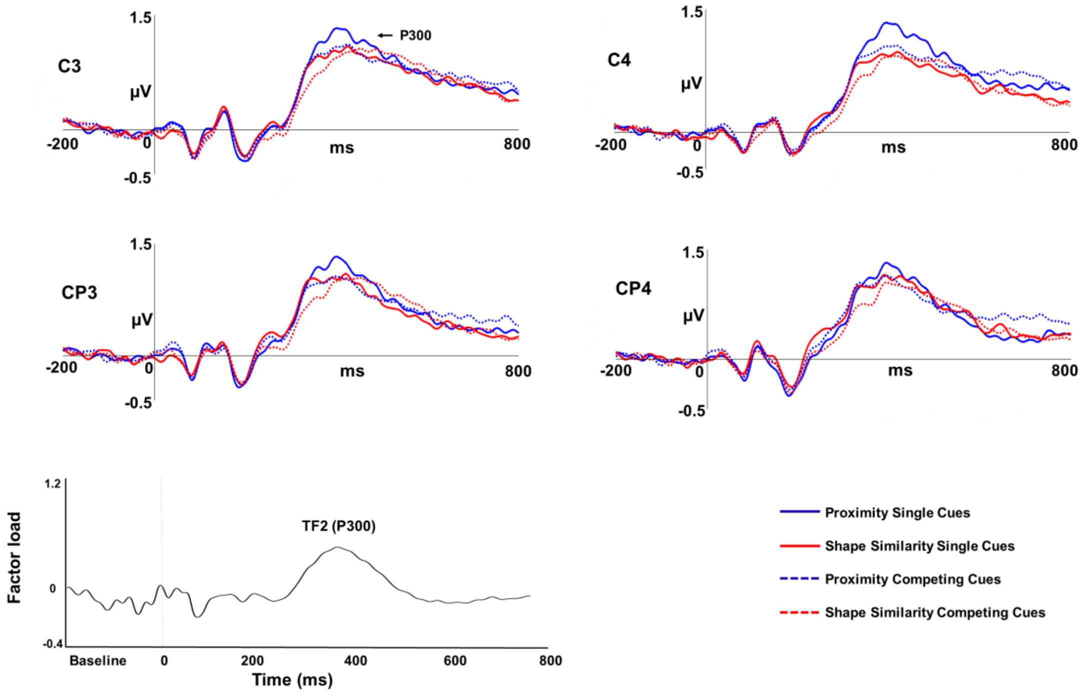


Figure 5. Grand averages of representative electrodes at central and parietal sites, where the experimental P300 effects are visible. Bottom: Factor load after promax rotation, temporal course and peak latency of FT2 (P300), which was extracted from the temporal principal component analysis. TF: temporal factor.

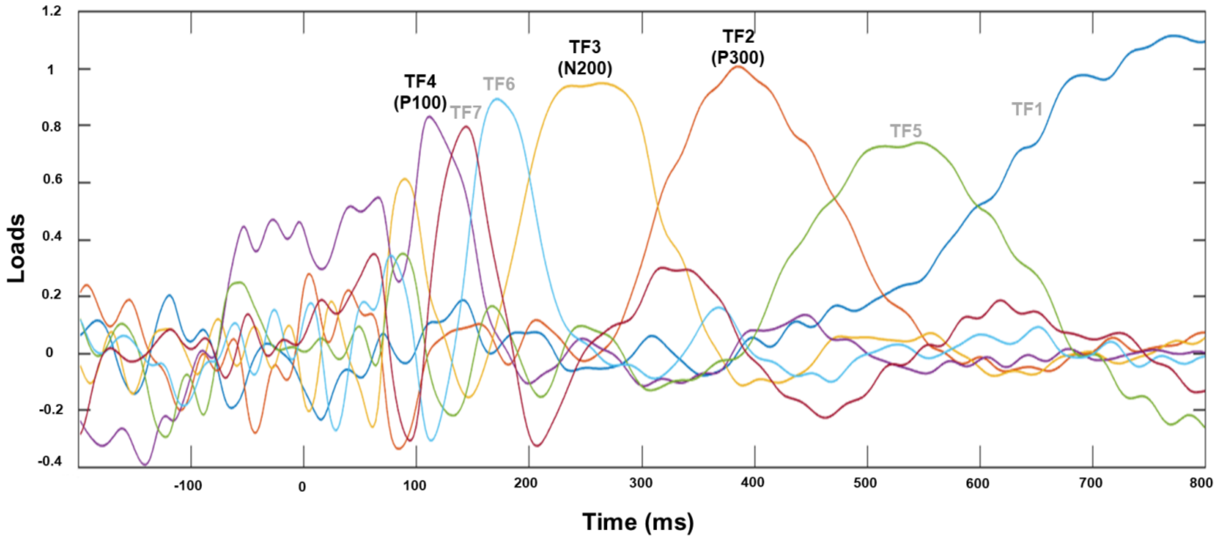


Figure 6. Temporal principal component analysis: factor loadings after promax rotation.: Temporal factors 4, 3, and 2 correspond to the P100, the N200) and the P300 components where experimental effects were predicted. TF: temporal factor.

The sPCA decomposed TF4 (P100) in 6 spatial factors (SFs), the TF3 (N200) in 5 SFs and the TF2 (P300) in 6 SFs. The topography of each of these factors is summarized in Table 2. Repeated measures ANOVAs on the SFs for Stimulus type (two levels: single or combined grouping cues) and Directed attention (two levels: to proximity or to shape similarity) were carried out as previously described. No significant main effects or interactions were found for the P100 in any of the SFs. Regarding the N200 a statistically significant interaction between Stimulus type and Directed attention was observed in parietal and occipital regions (SF 1). The results of post-hoc analyses indicated larger negative amplitudes for shape similarity cues in competing relative to single displays. Interestingly, the lack of differences when comparing proximity cues in competing and single displays indicates that this parieto-occipital N200 might be an index of the interaction between grouping principles. Finally, a main significant effect of Stimulus Type was found in central and parietal regions (SFs 3 and 4) for the P300. Also, a main effect of Directed attention was found at right central region (SF 4). Post-hoc analyses showed enhanced positive amplitudes for single compared to competing conditions, as well as larger amplitudes for proximity compared to shape similarity cues. Table 2 shows the results of these analyses. The topography of the significant P100 and N200 effects is shown in Figure 7.

Table 2. Statistical analyses performed on relevant ERP components associated with perceptual grouping extracted by temporo-spatial principal component analysis (PCA).

		ANOVA* (d.f. =1, 23)			
Temporal factor	Spatial factor	Main effect of Stimulus type	Main effect of Directed attention	Interaction	Post – hoc tests**
TF4 (P100)	Frontal	n.s.	n.s.	n.s.	
	Parieto-occipital	n.s.	n.s.	n.s.	
	Central-parietal	n.s.	n.s.	n.s.	
	Temporo-occipital	n.s.	n.s.	n.s.	
	Left Parietal	n.s.	n.s.	n.s.	
	Left Central	n.s.	n.s.	n.s.	

TF3 (N200)	Parieto-occipital	n.s.	n.s.	**F=6.996, p=0.014, η^2_p=0.233**	**Shape [a] Single>Competing**
	Fronto-parietal	n.s.	n.s.	n.s.	
	Left Temporo-parietal	n.s.	n.s.	n.s.	
	Right Central-parietal	n.s.	n.s.	n.s.	
	Fronto-central	n.s.	n.s.	n.s.	
TF2 (P300)	Fronto-parietal	n.s.	n.s.	n.s.	
	Parieto-occipital	n.s.	n.s.	n.s.	
	Right Central	**F=4.664, p=0.041, η^2_p=0.169**	n.s	n.s	**Single>Competing [b]**
	Centro-parietal	**F=7.731, p=0.011, η^2_p=0.252**	**F=13.388, p=0.001, η^2_p=0.368**	n.s	**Single>Competing [b] Proximity>Shape [b]**
	Temporo-parietal	n.s.	n.s.	n.s.	

Left Temporal	n.s.	n.s.	n.s.

Abbreviations: d.f., degrees of freedom; TF, temporal factor; SF, spatial factor; n.s., no significant.

* Repeated-measure ANOVA with stimulus type (two levels: single and competing) and directed attention (two levels: proximity cues and shape similarity cues) as a factors. Given the large number of test involved, a Bonferroni was applied. *p*-Values reported in the table are Bonferroni-corrected for multiple comparisons.

** Significant main effects and interactions were further decomposed using post-hoc comparisons with a Bonferroni correction. Significant results were those with Bonferroni corrected *p*-values < 0.05.

[a] The occipito-posterior N200 showed larger amplitude for shape similarity than for proximity cues. Shape similarity single cues elicited large positive amplitudes whereas competing conditions are associated to a more negative amplitude.

[b] The posterior P300 reveal a larger positive amplitude for single conditions and only related to proximity single cues.

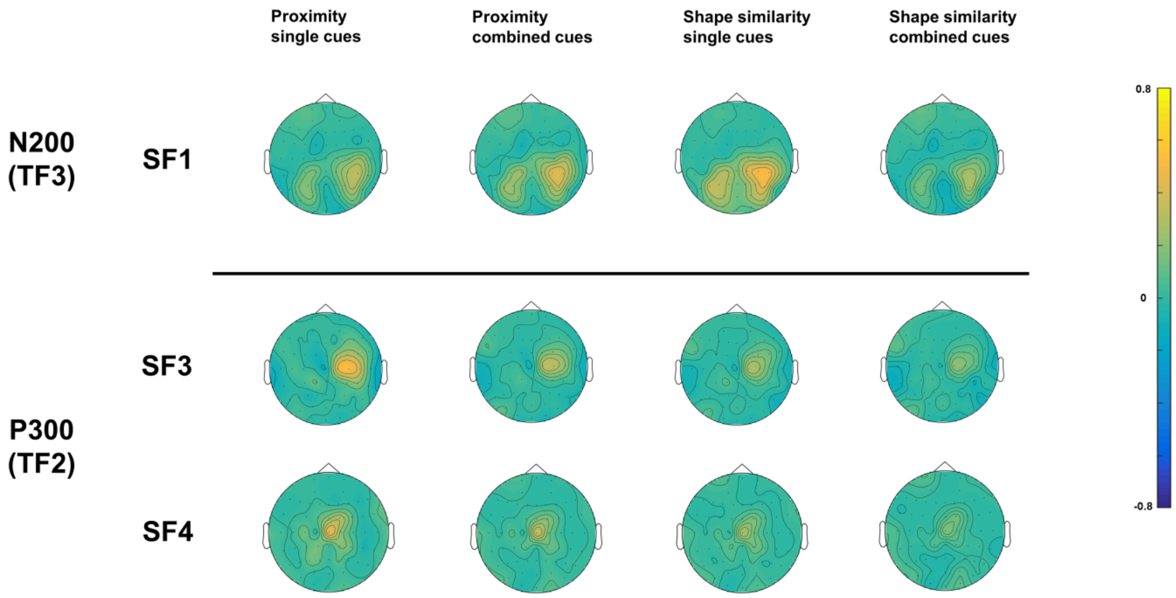


Figure 7. Spatial factors extracted for the temporal factors 3 (N200) and 2 (P300) through principal component analysis (sPCA). Only those spatial factors that were sensitive to the experimental manipulations are shown. The color scale represents spatial factor scores. The four experimental conditions are shown. TF: temporal factor; SF: spatial factor.

3.4. Discussion

In the current study, we examined the temporal brain signatures of the dominance of single and competing intrinsic grouping cues by means of two highly representative grouping factors, namely proximity and shape similarity. In particular, we predicted that the two competing principles would interact around 200 ms (before the stimulus presentation), as reflected by the modulation of a negative component with a posterior topography, in line with the results reported by Han (2004). To this aim, we used a selective attention to grouping cues task that allows examining the dominance dynamics of competing organizations: the relative advantage of single grouping cues and the pattern of interference when two competing grouping cues are conjoined in the same pattern (Luna et al., 2016). In the current study, we found that the effects of advantage and interference show a dissociated pattern, which is in line with prior studies on processing dominance (Amirkhiabani & Lovegrove, 1999; Lamb & Robertson, 1988). Our behavioural results indicated a consistent pattern for both RTs and accuracy. An advantage effect was found for proximity that was associated with faster and more accurate responses relative to shape similarity when single cues were compared. However, the interference effect between competing grouping cues indicated that proximity was more interfered by the presence of shape similarity than vice versa. In this line, we found faster and more accurate responses for single grouping conditions compared to the competing condition. Interestingly, this interference effect was bidirectional and asymmetrical since the magnitude of the interference of shape similarity on proximity was larger than vice versa. Despite this asymmetrical interactive effect, the results of our analyses suggested that the non-attended proximity cue was still perceived and was not entirely suppressed, since the interference effect of proximity on shape similarity was also statistically significant for both RTs and accuracy. Thus, our data suggest that when more than one organization is possible in a visual pattern, all the different perceptual alternatives are represented to some extent in the visual system. Consequently, they compete for the dominance of grouping cues (Luna et al., 2016; Rashal et al., 2017). Similar results were observed in the study by Luna and co-workers (see Exp. 1), although the interaction between factors only showed a trend towards significance. The increased number of trials (480 vs 256 trials), as well as the larger sample size (24 vs 16 participants) included in the current study compared to the study by Luna et al. (2016) might partially explain differences in behavioural data.

Previous research has found that grouping by proximity and by shape similarity are associated with different time courses (e.g., Ben-Av & Sagi, 1995; Han and Humphreys, 1999) and distinct ERP correlates (e.g., Han, 2004; Han et al., 2001, 2002). Studies exploring interactions between intrinsic grouping cues reported larger amplitudes in a positive component peaking around 100 ms in occipital electrodes for proximity grouping cues (Han, 2004; Han et al., 2001, 2002). This finding led the authors to conclude that grouping by proximity depends on the representation of spatial relationships between local elements, which are independent of visual features such as the shape or the colour of discrete elements. To our knowledge, only one previous study has examined the ERP correlates of the competition between shape similarity and proximity (Han, 2004). An enhanced positivity between 100 and 140 ms for proximity cues relative to similarity cues was found in this study. In contrast, we did not observe amplitude differences between proximity and shape similarity in this time window. The discrepant results might be related to differences in the configuration of the displays used in both studies. In this sense, in the present study, we used the same stimuli in both the proximity and the shape similarity competition conditions, so perceptual processes were modulated by task demands in the absence of differences in the perceptual organization of the displays. In contrast, Han (2004) displayed different stimuli in the congruent and incongruent conditions, which could partially account for differences in P100 amplitudes. Also, the grouping strength of the principles was not controlled for in the study by Han (2004). In order to control for this parameter, in our study we used the same stimuli as in Luna and Montoro (2011), which reported no differences between proximity and shape similarity cues in a phenomenological measure of grouping strength. Nonetheless, it should be noted that the matching of grouping strength was done by a different sample of participants and previous studies have reported interindividual differences in perceived grouping strength (Claessens & Wagemans, 2005).

Although null findings should be always interpreted with caution, our data suggest that the early processing of proximity and similarity grouping cues share some aspects when these principles compete. In fact, prior evidence has shown that the P100 might characterize external properties of the stimulus regardless of the grouping principle (Nikolaev & Van Leeuwen, 2004). Thus, in our study, similar P100 effects for the two grouping cues might reflect the operations related to contour interpolation, which are needed for the perceptual completion of squares and circles in both the shape similarity and proximity competing conditions. In this line, P100 effects in posterior electrodes have been reported during contour illusory processing (Murray et al., 2002; Nikolaev & Van Leeuwen, 2004).

Remarkably, the first electrophysiological evidence of the interaction between proximity and shape similarity cues peaked around 250 ms at parieto-occipital electrodes. This rather middle latency effect is in accordance with prior proposals which claim that when different configurations are in conflict, both grouping organizations are processed equally until one of them dominates the perceptual interpretation of the display (Rashal et al., 2017). In agreement with the prediction based on Han (2004), our results showed enhanced N200 amplitudes in the single shape similarity condition compared to the competing similarity condition. In contrast, no differences in N200 amplitudes were observed between single and competing trials in the proximity conditions. In the study by Han (2004), the interaction between proximity and shape similarity cues modulated the amplitude of a negative ERP component between 180 and 220 ms in posterior electrodes (i.e. larger amplitude in congruent than incongruent trials in the shape similarity block and no differences between proximity conditions; Han, 2004, pag. 42). In line with these findings, our N200 effect could be interpreted as a brain index of the visual salience and/or the processing fluency of shape similarity grouping. Consequently, the enhanced amplitude elicited by the single condition may reflect an easier processing of the shape similarity grouping cue when organizing the visual pattern relative to the competing condition, which involves interference effects from alternative grouping operations based on the non-attended proximity cue. Consistently with this interpretation, previous research has reported that grouping by shape similarity is reflected in a long latency occipito-temporal negativity within this time interval (Han, 2004; Han et al., 2001, 2002, 2005; Han & Humphreys, 2007; Mao et al., 2004). Crucially, the modulation of this ERP component represents an indirect brain hallmark of the competitive interaction between grouping cues, which could be explored in future studies with other principles in order to determine how single grouping cues interact when they are conjoined, especially in a competitive manner.

Finally, we found effects in a positive component peaking around 380 ms (P300) with a centro-parietal distribution over the scalp. In particular, single displays elicited larger positive amplitudes relative to competing displays in both proximity and shape similarity conditions. Modulations of this component during single cues processing have been previously related to integrative processes joining perception to action, which reflect the operations that take place between the identification of the stimulus and the selection of a response (Squires et al., 1975; Verleger et al., 2005). Additional evidence for this view comes from the results of a recent study that reported an association between perceived confidence in perceptual decisions and the P300 amplitude in a visual discrimination task (Zizlsperger et al., 2014). Therefore, the larger P300 amplitude in our study may be associated with higher certainty in the perceptual decisions made by the participants in the single trials relative to the competing condition (Montoro et al., 2015). In line with this proposal, we also found shorter RTs and more accurate responses for single compared to competing displays. Additionally, proximity grouping cues elicited larger P300 amplitudes than shape similarity cues, which is congruent with the finding of faster and more accurate responses for proximity compared to shape similarity single cues. Interestingly, no P300 amplitude differences between proximity and similarity cues were observed in the study by Han (2004), even though speeded RTs for proximity relative to similarity displays were found. Taking into consideration the divergence between ERPs and behavioural results, the author provided an interpretation of his findings in terms of perceptual factors such as delayed stimulus evaluation and categorization or motor factors such as slowed response selection and execution (Han 2004, pag. 43). In the current study, the similar pattern of results found for the P300 amplitude and the behavioural performance argues in favour of the association of this brain effect with confidence decisions during response selection.

In sum, up to date research on the competition between perceptual grouping cues is rather scarce. In the present study, we aimed to fill this void in research by examining the temporal brain dynamics of the dominance of single and competing proximity and shape similarity grouping cues. An important finding of the present study was the modulation of a N200 component by the interactive effect between the grouping cues. This electrophysiological correlate seems particularly sensitive to the perceptual fluency of shape similarity cues and, indirectly, also reflects the interfering effect of the unattended proximity cue in the competing condition. From a more general view, this finding introduces a brain index of the integration between Gestalt grouping cues and delimits the temporal occurrence of the competition about 250 ms after the stimulus presentation, at least for the specific grouping factors studied. Besides, we reported an enhanced posterior P300 for single relative to combined displays, which could reflect higher confidence decisions related to response selection. Additional research is needed to clarify whether the current findings generalize to other grouping principles, both intrinsic and extrinsic.

4. Experimental Study II

Villalba-García, C., Jimenez, M., Luna, D., Hinojosa, J.A., Montoro, P.R. Study on dissociations between measures of perceptual grouping: An integrative approach. (Submitted)

Abstract

We examined the competition dynamics of two intrinsic grouping cues (proximity and luminance similarity, Exp. 1, n = 127) and two extrinsic grouping factors (common region and element connectedness cues, Exp. 2, n = 52) through two different experiments. Previous studies have reported dissociations between different measures of perceptual grouping strength, claiming that a prior adjustment of grouping strength of each cue based on phenomenological judgments does not ensure that grouping operations are represented in an equivalent manner by the visuomotor system. In our study, observers performed a scaling task (phenomenological reports) in which they had to match grouping strength between both principles in interaction. Then, we introduced a complementary objective equating task to try again to equate prior grouping strength of each principle, but on this occasion based on RTs. Subsequently, participants completed a repetition discrimination task (RDT) in which two principles competed. Our results indicated larger interference effects of luminance similarity on proximity cues when both cues compete (Exp.1), as well as, a dominance effect of common region over connectedness cues in competing displays (Exp. 2). Dominance of common region or luminance cues has emerged, even after introducing a prior objective equating phase. However, all participants did not match RTs between single cues in the previous task, and those that did, in RDT their data fit the same pattern of performance regarding global sample. Likewise, our analyses based on subgroups of participants underline the importance of examine individual differences in the context of visual perceptual organization.

Keywords: Gestalt; Competition; Grouping by common region; Grouping by connectedness; Grouping by proximity; Grouping by luminance similarity.

4.1. Introduction

Perceptual grouping operations are essential for visual object recognition. Proximity, similarity, common fate, closure or good continuation are some of the *laws* proposed by Gestalt psychologists in the early 20th century, from the seminal work of Wertheimer (1923), in order to explain how our visual system organizes elements that conform the visual scene (see Wagemans et al., 2012a, for a review). Other grouping principles have been later proposed, such as common region or element connectedness (Palmer, 1992; Palmer & Rock, 1994) (see Brooks, 2015 for a review). Palmer (1999) suggested reclassifying all these principles into two clusters: (1) *intrinsic* grouping cues, which are rules based on built-in properties of discrete elements, whereas, (2) *extrinsic* cues are based on relationships between individual elements and other external cues that induce them to group. As an example, similar elements equally spaced in a display tend to be grouped together when they are located within the same spatial region (i.e. grouping by common region; Palmer, 1992).

A relevant research topic in this field concerns the integration between grouping principles when they are conjoined in the same visual pattern, and more specifically their competitive interactions (e.g., Luna & Montoro, 2011; Luna et al., 2016; Montoro & Luna, 2015; Montoro et al., 2017). In general, prior results pointed out stronger and more stable grouping effects when two cues cooperate and weaker and unstable effects when they compete, compared to grouping effects found for each single principle. It is suggested that when two grouping cues compete, the non-dominant cue is perceived to some extend and thus it is not completely inhibited (Luna et al., 2016; Rashal et al., 2017). Both findings are compatible with an additive model of the interactions between grouping principles (Kubovy & van den Berg, 2008).

Nonetheless, although more research is needed to unravel these operations underlying interactions between different cues, classical research has focused on the study of relationships between intrinsic principles (see Peterson & Kimchi, 2013, for a review). In particular, several studies have been conducted based on relationships between the classic principles such as proximity and similarity cues (e.g., Ben-Av & Sagi, 1995; Claessens & Wagemans, 2005; Claessens & Wagemans, 2008; Kubovy & van Den Berg, 2008; Luna & Montoro, 2011; Luna et al., 2016; Oyama & Miyano, 2008; Quinlan & Wilton, 1998; Schmidt & Schmidt, 2013; Villalba-García et al., 2018; Zucker, Stevens & Sander, 1983). For instance, Hochberg and Silverstein (1956) studied in the 50s, the interaction between proximity and luminance similarity cues. They displayed rectangular patterns formed by coloured squares containing different luminance values. Observers had to adjust distances between squares trying to match the grouping strength of proximity cues with respect to luminance cues. A later reanalysis of Hochberg and Silverstein (1956) data carried out by Kubovy and van den Berg (2008), revealed an additive cooperative effect between proximity and luminance similarity cues. Ben-Av and Sagi (1995) examined competition interaction between different intrinsic cues. They manipulated luminance similarity, shape similarity and proximity cues. In their displays two cues competed, as participants could perceive for example, columns grouped by luminance similarity or rows by proximity cues simultaneously. In their studies they controlled the stimulus onset asynchrony (SOA) between masks and the stimuli used as a target. The task consisted of report the perceived orientation of one possible organization (horizontal vs. vertical) which let to measure dominance between different grouping cues and determine their time course. They reported proximity dominance for shorter SOAs, as it was perceived under shorter exposure times. However, Dominance exerted by shape and luminance similarity cues emerged under longer SOAs. Quinlan and Wilton (1998) examined relationships between proximity and similarity (luminance similarity and shape similarity) cues. Their stimuli were composed of a row of seven geometric figures, whose central element was the target. Participants had to use a numerical scale to rate the degree of grouping they perceived between the central element and other three elements located to its left or its right, in each trial. The grouping of the central element was guided by these different underlying grouping cues. They found that although proximity seems to be dominant, it can also be neutralized by similarity cues. Later Kubovy and van den Berg (2008) explored interactions between proximity and luminance similarity cues. For this, they used rectangular dot lattices. Dots with same contrast were arranged along the longer axis (proximity and similarity in cooperation) or arranged along the shorter axis (proximity and similarity in competition). Dot lattices varied into two dimensions: (i) ratio between short and long axes of each rectangle of dots within the lattice and (ii) differences in contrast between the different arrays of dots. Observers had to identify which one of four possible orientations corresponded better to an agreed-upon arrangement of the dots in the lattice. In conclusion, they obtained a function that predicts how grouping by proximity varies depending on the relative distance between axis. Similarly, the effects found related to cooperation between both grouping factors were considered as additives.

In recent years, nonetheless, principles of extrinsic grouping have been included in the study of interaction between different cues. Luna and Montoro (2011) examined interactions between intrinsic grouping cues (i.e. proximity or shape similarity) and extrinsic grouping cues (i.e. common region cues). They presented these principles acting alone or conjoined (cooperation or competition displays). Participants were instructed to rate the degree to which the central element grouped with either the right or the left flanking elements on a 9-point rating scale. Their results showed that observers rated common region as stronger than proximity cues in competing displays. However, they did not find grouping effects when similarity cues (as luminance or shape) interacted with common region cues. In any case, they affirmed that the pattern found on the interactions between intrinsic and extrinsic principles mirrored those pattern between intrinsic principles interactions already found in previous literature. Montoro et al. (2015) used a perceptual discrimination task and they found that luminance similarity cues were answered more slowly and less accurately than common region cues. Luna et al. (2016) used a paradigm in which participants selectively attended to different perceptual groups and also reported a clear dominance of common region cues: in competing conditions, responses guided by connectedness or by shape similarity cues were slowed by the presence of a competing common region cue more than vice versa. Montoro et al. (2017) showed that grouping by common region dominated display organization when it compete against connectedness. In this case, they used the repetition discrimination task (RDT, Palmer & Beck, 2007), which indirectly examines the influence of underlying grouping principles when participants search for a repeated pair of adjacent discrete elements (i.e. circles or squares) within a longer series of nine elements. Prior to RDT, a subjective scaling task was carried out in which each participant individually adjusted the grouping strengths of both principles in order to equate them on a phenomenological level. Their results pointed out that, even when the grouping strength of common region and element connectedness was phenomenologically equated, responses in the RDT were still faster in single common region compared to single element connectedness condition. Interestingly, these authors carried out an exhaustive inspection of individual data (see supplementary materials, p. 7, from Montoro et al., 2017) and although they observed heterogeneous ratings on individual responses in these phases prior to RDT (even a participant obtaining fasters RTs to single connectedness respect to common region) they found a consistent and systematic dominance of common region over connectedness in competing conditions of the RDT. Overall, the revised evidence on dynamics of competing perceptual grouping cues suggests that common region gains dominance over other principles independently of the nature of the measure used. Remarkably, in all these cited studies, phenomenological grouping strength was previously equated, as prior literature strongly recommends (e.g., Kubovy & van den Berg, 2008; Montoro et al., 2015).

Recently, Schmidt and Schmidt (2013) studied competition interactions between intrinsic grouping cues using a primed flanker task. They found that grouping by shape similarity caused bigger priming effects than grouping by size or luminance similarity, regardless of prior phenomenological adjustment of grouping strength of each grouping cue (scaling task). Interestingly, these authors suggested that probably perceptual parameters determining grouping strength of the different cues were differently processed at phenomenological and visuomotor levels. Consequently, this dissociation between subjective (i.e. the scaling) and objective (i.e. the primed flanker task) visual measures suggests the need of new procedures in order to equate grouping strengths of different cues at both subjective (i.e. phenomenological) and objective (i.e. visuomotor) levels.

Our goal is to examine competition dynamics between different intrinsic and extrinsic grouping cues by means of an indirect task (i.e. the RDT, Palmer & Beck, 2007) which provides an unbiased measure of the competition between grouping principles based on reaction times (RTs) and accuracy rates. In Experiment 1, relationships between two classic intrinsic principles- proximity and luminance similarity- was explored. While in Experiment 2, interactions between two extrinsic principles -common region and connectedness- were examined. Palmer and Beck (2007) have previously examined interactions between intrinsic principles in their experiments, but they did not explore competitive interactions. On the other hand, prior reports have consistently shown that common region dominates over different grouping cues, and we considered relevant to explore whether this effect continued to be stable after the introduction of an objective equating phase. We decided to study competition between luminance similarity and proximity cues (Experiment 1) because manipulate luminance similarity does not alter spatial relationships between discrete elements, which therefore does not affect proximity dimension and vice versa. In fact, proximity cues could be manipulated as well as distance between elements increase or decrease. Extrinsic principles examined in Experiment 2 are based on spatial relationships that include a third external element, such as ovals or lines, that induce these discrete elements to be grouped. Carried out two different experiments based on relationship between different grouping cues, guarantees in a certain way that the effects found are not due to the physical parameters related to manipulations in the stimuli.

Our main contribution is the inclusion, for the first time, of an *objective* equating phase prior to RDT. As in previous studies, we firstly conducted a subjective *scaling task,* which allowed to obtain individual grouping strength values for each participant based on their subjective judgments about match grouping strength between two principles in interaction. Secondly, we introduced an *objective equating task* phase, where participants had to perform an RDT but with an important restriction: only single grouping cues acting alone were displayed in each trial (Figure 1B and Figure 3B). It was assumed that both grouping cues were objectively equated when differences in average RT was lesser than

10 ms between both conditions. This interval has been chosen by researchers adopting a conservative criterion, so that reaching a difference of less than ten milliseconds, we ensure that both principles are equated in performance and therefore in its grouping strength. Finally, RDT include competing conditions displayed in a personalized stimulus set. The purpose of the objective equating task was to ensure that the grouping strength for both principles was equated at the visuomotor level. Given the introduction of an objective equating phase in both experiments, we expected that equate grouping strengths in the objective equating task (visuomotor system) would result in an absence of differences between competing conditions of RDT. Similarly, we expected to replicate prior results (e.g., Luna et al., 2016; Villalba-García et al., 2018) as single displays should be answered faster and more accurately than combined displays, no matter which grouping principle is involved.

4.2. Experiment 1. Proximity and Luminance Similarity

4.2.1. Method

4.2.1.1. Participants

One hundred twenty-seven undergraduate students (31 men; age range: 19-60 years, M = 30.98, SD = 10.18) from the UNED participated in the study. All of them received course credits for their participation in the experiment and they had normal or corrected-to-normal vision. The experimental procedure was approved by the Local Ethics Committee and conforms to the Declaration of Helsinki.

4.2.1.2. Apparatus

The stimulus patterns were displayed on a 19-inch (c.48.25-cm) LCD-LED colour monitor with a 75-Hz refresh rate, a 5:4 aspect ratio, and a resolution of 1280 x 1024 pixels, controlled by a personal computer running E-Prime 2.0 software (Psychology Software Tools, 1996 – 2013). Viewing distance was nearly 60 cm. Responses were recorded using a standard keyboard.

4.2.1.3. Stimuli

The stimuli set was inspired by Palmer and Beck (2007), specifically in the Experiment 1 and Experiment 3.

In the scaling task, all of stimuli were competing patterns which alternated square/circle shapes in absence of target pairs (Figure 1A). The shapes used were squares (10 mm x 10 mm) and circles (10 mm in diameter). The shapes were black (RGB: 0; 0.06 cd/m2) or white (255 RGB; 86.3 cd/m2) and were presented on a grey background (192 RGB; 26.6 cd/m2). Twenty different stimuli were designed by manipulating the distance between the elements from 10 to 28 pixels by two-unit increments (pixels 10 to 28). We obtained 20 displays due to the experimental counterbalance.

In the objective equating phase, the stimuli were the same 32 patterns displayed in the RDT phase for the single conditions (Figure 1B, described below in the RDT task). The value assigned to proximity conditions was selected from the scaling task phase, customized for each participant.

For the RDT phase, 64 different stimuli were drawn (Figure 1C): 32 displays for single conditions and 32 for competing conditions. In luminance similarity single condition, the nine elements alternated between circles and squares, except for a single pair of adjacent similar shape. The fixed distance between pairs of elements will be maintained. The elements could be white (255 RGB; 86.3 cd/m2) or black (RGB: 0; 0.06 cd/m^2) interleaved. In some trials, the two underlying elements might share the same luminance value, while in others they did not. In proximity single condition, the nine elements alternated between circles and squares, except for a single pair of adjacent similar shape. In some trials all the elements would be white (255 RGB; 86.3 cd/m2) while in others all would be black (RGB: 0; 0.06 cd/m^2) displayed on a grey background (192 RGB; 26.6 cd/m2). In this condition the elements were closer to each other two to two (except one element at the end, right or left according to the trial) (see Figure 1C). In some trials the two consecutive equal elements could be contained in the same pair of proximal elements, while in other trials they could be in different pairs. The distance value between elements was adapted for every single participant and based on the results of the objective equating phase. In the competing conditions, both luminance and distances were included as a part of the stimuli (Figure 1C).

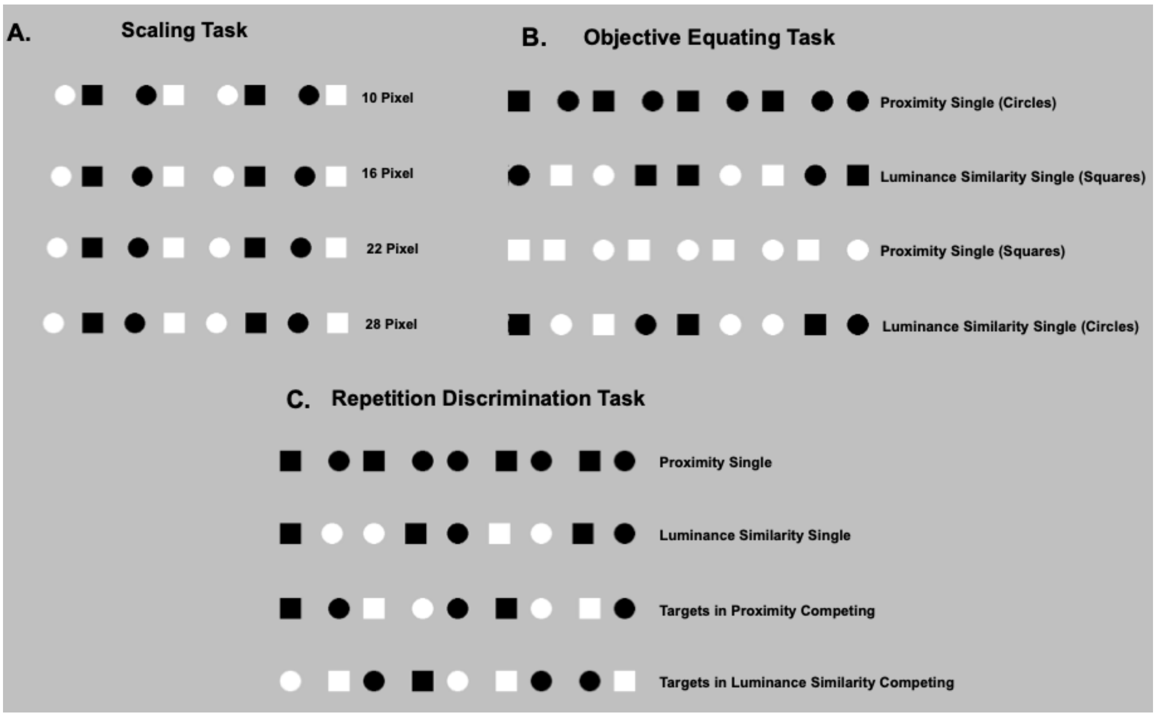


Figure 1. Examples of stimuli displayed in the **(A)** Scaling Task **(B)** Objective Equating Task **(C)** Repetition Discrimination Task. The distance between elements (proximity conditions) is equal to 20 pixels related to the Objective Equating Task and Repetition Discrimination Task.

4.2.1.4. Design and procedure

The 2x2 design included two within-subject factors: Stimulus type *(single or competing grouping cues)* and Grouping cue *(proximity or luminance similarity)*. These four different types of stimuli were combined with six different positions of the target pair (elements 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, counting from the left), two shapes of the target pairs (circles vs. squares) and two repetitions in order to obtain a total number of 128 trials for each experimental block. Dependent variables measured were reaction times (RTs) and error rates (ACC).

Participants were individually tested in a quiet room in three different phases: (1) scaling task, (2) objective equating task and (3) RDT. In the scaling task, participants had to manipulate the distance of the elements until their grouping strength seemed as equally strong as the grouping strength of the luminance cue, so that the visual grouping of the elements in pairs were equally salient in figures closer to the others. Participants performed one practice trial and eight scaling trials: four trials starting with 10 pixels in distance (i.e. *ascending* trials) and the other four beginning with 28 pixels in distance (i.e. *descending* trials). The order of presentation of the trials was counterbalanced between subjects. Participants manipulated the values of the distance by pressing the right (to increase the distance) or left arrow (to decrease the distance) keys of the keyboard with the index fingers of both hands. There was no time limit. When they were sure of their decision, they had to confirm by pressing the space bar to continue to the next trial. Participants were not informed about the value of the distance. Taking the eight values recorded, an average value was calculated for each participant. The mean value was implemented as the distance value between elements in the stimuli displayed in the subsequent objective equating task.

In the objective equating task, the separation between elements value of the scaling phase was used as the starting criterion and participants were required to indicate the shape of the repeated pair of elements (circle or square), as fast as possible while avoiding errors, by pressing one of two keys ("Z" and "M", respectively) using their left or right index. The stimulus array displayed on the centre of the screen remained until response. The inter-trial interval was 800 ms. In this phase, there were only two experimental conditions, single proximity and single luminance similarity cues. In each block, the average value of correct RT trials for each experimental condition was obtained. When average RT differences between grouping cues were higher than 10 ms, the software added (or subtracted) a pixel to the distance of the proximity cue, depending on whether the participant responded faster (or slower to) proximity cues compared to luminance similarity. When average RT differences between conditions were less than or equal to 10 ms, it was assumed that both principles were equated for the visuomotor system. In this case, the pixel distance value was recorded and later used for the RDT phase. Participants could perform up to 10 experimental blocks, with a total of 320 experimental trials (160 trials for single proximity and 160 for single luminance similarity cues). There was a practice block with 32 trials and feedback was provided only for those practice trials. If after the 10 experimental blocks, the average RT differences between grouping cues were not less than or equal to 10 ms, the distance values of the last block were used for the RDT phase.

Finally, in the RDT, the value of the distance between elements was taken from the objective equating task. Instructions (see Appendix II) were the same as the previous phase *(objective equating task)*. In this phase, there were four experimental conditions, namely: two single conditions (one displaying proximity cues and another one with luminance similarity cues) and two competing conditions (one with targets grouped by proximity and another one with targets grouped by luminance similarity). The stimulus array was displayed on the centre of the screen and it remained until response. The inter-trial interval was 800 ms. There was a practice block with 24 trials, where feedback was provided, and four experimental blocks of 128 trials each, for a total of 512 experimental trials.

4.2.2. Results and discussion

4.2.2.1. Scaling task

Mean pixel adjusted values varied between 10 and 28 (mean = 22.34; SD= 3.9). Data showed a great variability among participants' judgments in their perception of relative grouping strength.

4.2.2.2. Objective equating task

In this phase, pixel values were found in the range from 10 to 28 pixels (mean = 24.46; SD= 4.3). Fifty-six participants equated the grouping strengths of the different cues, whereas seventy-one participants did not reach a RT difference of ± 10 ms between single grouping cues.

4.2.2.3. Repetition discrimination task

Median RTs of correct responses and mean accuracy rates were submitted to separate analyses of variance (ANOVAs) with Stimulus type and Grouping cue as within-subject's factors.

RT analysis. RTs less than 200 ms and greater than 4000 ms (64172 of 64900; 1.2 % of trials) and inaccurate responses (63049 of 64900; 2.8 % of trials) were not included in the RT analyses.

Analyses of RTs showed a significant main effect of Grouping cue, $F(1,126) = 402.2$, $MSE = 9980333$, $p < .001$, η_p^2= . 0,761, pointing out that RTs for proximity cues (1056 ms) were larger than those for luminance cues (776 ms). The main effect of

Stimulus type was significant, $F(1,126) = 1179.4$, $MSE = 14461031$, p < .001, $\eta_p^2 = .903$, indicating that single grouping cues were responded faster (747 ms) than competing grouping displays (1084 ms). Finally, the interaction between the two factors was significant $F(1,126) = 535.7$, $MSE = 11687028$, $p < .001$, $\eta_p^2 = .810$, showing that the difference between luminance single and proximity single conditions was significantly smaller (Δ 23 ms: 759 – 736 ms) than between both competing conditions (Δ 618 ms: 793 - 1377 ms). The difference between competing conditions is much greater than that obtained between the single conditions of both interacting principles. This fact could be interpreted as an interactive or emergent effect that cannot be explained by the strength of each principle in isolation, which does not seem to be compatible with an additive model. Pair-wise comparisons making use of Bonferroni correction displayed significant differences between all pairs from the experimental conditions (all of them $ps \leq .001$).

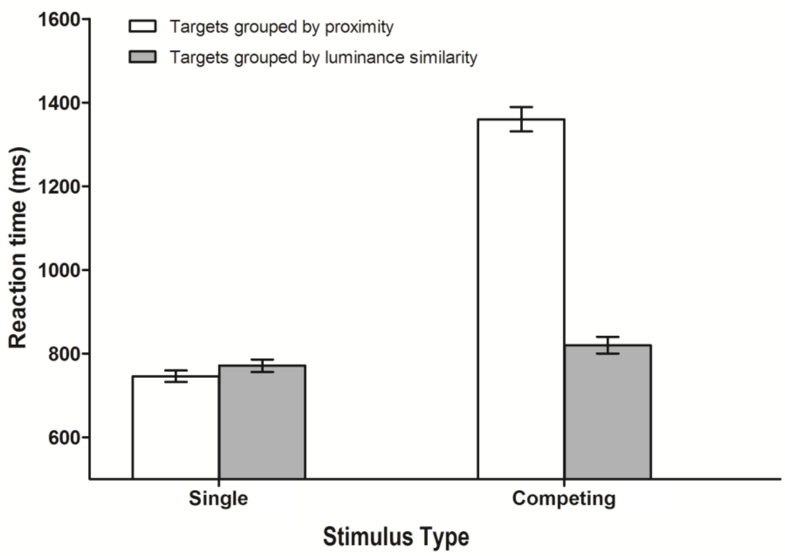


Figure 2. Mean reaction times *(ms)* and standard error bars for the experimental conditions of the RDT.

Our RT analyses showed significant differences between single conditions in the RDT phase, which indicates that in spite of having participants that have equated both principles through the visual motor system, it has not been possible to find this effect in the entire sample. Given that fifty-six participants managed to obtain a difference equal to or less than ten milliseconds by responding to both principles in the objective equating task, it is questionable whether any of these participants subsequently obtained significant differences in the RTs of the conditions of the RDT.

In order to further explore the relationship between the repetition discrimination task (RDT), the scaling task and the objective equating task, we introduce a table **(Table 1)** that collects individual performance.

Table 1. Individual responses and mean values to the RDT, scaling task and objective equating task. Differential variables to the RDT and objective equating task.

	Single conditions		**Competing conditions**								
Subject	**PR**	**LU**	**PR**	**LU**	**Diff. Singles RDT PR - LU**	**Diff. Competing RDT PR-LU**	**Scaling task mean values**	**Objective Equating task mean values**	**Objective Equating PR**	**Objective Equating LU**	**Diff. Objective Equating PR-LU**
1	742	713	1116	904	29	213	10	14	853	932	-79
2	761	757	1279	812	4*	468	13	22	802	993	-191
3	594	627	1028	673	-33	355	22	22	654	633	21
4	804	781	1290	807	24	484	23	26*	920	911	9
5	714	773	1143	1040	-59	103	16	18	1104	1261	-157
6	808	812	1235	780	-4*	456	26	28	832	853	-21
7	665	738	1610	692	-73	918	28	28	782	884	-102
8	759	740	1897	729	19	1.168	21	28	804	930	-126
9	678	807	1300	874	-130	426	17	18*	807	799	8
10	801	826	1216	845	-25	371	20	22	950	1058	-108
11	755	800	1096	1445	-45	-349	22	16	883	1081	-198
12	601	607	1290	626	-7*	664	15	24	611	658	-47
13	725	714	1315	657	11	658	25	28*	688	694	-6
14	616	651	942	633	-35	309	22	24*	625	624	1

15	572	629	1035	716	-57	320	15	14*	733	735	-2
16	817	787	1458	798	30	661	27	26*	958	957	1
17	761	808	1453	777	-47	676	24	28	1022	1131	-109
18	810	761	1468	814	49	654	21	26*	877	883	-6
19	783	822	1179	791	-39	388	17	22*	813	813	0
20	679	709	1181	717	-30	464	27	28	714	808	-94
21	554	576	1386	561	-22	825	24	28	501	645	-144
22	764	792	1171	877	-28	294	22	22*	738	742	-4
23	742	833	1461	768	-92	694	24	24*	888	879	9
24	691	731	1084	1001	-40	83	18	16	929	913	16
25	699	692	1479	720	7*	760	23	28	687	721	-34
26	1005	1047	1430	1041	-43	389	26	28*	1149	1143	6
27	756	761	1233	757	-5*	477	24	24*	970	964	6
28	701	696	1554	733	5*	821	23	28	711	802	-91
29	624	684	1220	630	-61	590	22	22*	648	653	-5
30	589	634	1016	760	-46	256	17	18*	741	745	-4
31	706	765	1466	789	-59	677	23	20	760	946	-186
32	806	775	1675	787	32	889	23	28	759	816	-57
33	702	682	1436	689	20	747	20	26	727	788	-61
34	638	636	1091	643	2*	448	23	28	627	696	-69
35	592	647	1311	594	-55	718	22	26	792	726	66
36	652	672	1460	662	-20	799	21	28	578	669	-91
37	756	774	1626	780	-18	846	20	28	971	1185	-214
38	831	876	1818	867	-45	951	22	28	788	916	-128
39	662	701	1056	774	-39	282	19	18*	766	774	-8
40	821	785	1929	782	36	1.147	20	28	1053	1694	-641
41	768	737	1957	722	31	1.235	18	24*	839	830	9
42	727	735	1580	762	-9*	818	23	28*	760	756	4
43	693	754	1671	740	-61	931	26	28	825	958	-133
44	570	597	1054	577	-27	477	26	28	646	696	-50
45	647	653	987	680	-6*	307	23	24	720	801	-81
46	793	798	1361	770	-5*	592	28	28	889	950	-61
47	813	820	1780	826	-7*	955	23	24*	1017	1010	7
48	826	774	1904	777	52	1.127	28	28	962	1143	-181
49	717	750	1006	840	-33	166	12	18	798	685	113
50	1094	1031	1636	1475	64	161	17	16*	1302	1312	-10
51	891	846	1833	862	45	972	20	28	1091	1272	-181
52	1695	1895	2234	1741	-200	494	17	22	4530	3872	658
53	798	837	1400	814	-39	587	24	24*	1551	1549	2
54	657	691	1216	651	-34	565	24	28	574	661	-87
55	833	836	1395	826	-3*	569	20	28*	581	574	7
56	749	747	1367	751	2*	617	24	28*	778	783	-5
57	847	870	1440	881	-24	559	23	22*	920	927	-7
58	805	816	1297	868	-12	429	22	18*	854	855	-1
59	709	684	1383	732	25	651	25	28*	784	778	6
60	682	696	1180	726	-14	454	20	22	895	808	87
61	684	736	1368	793	-52	576	28	26	753	1146	-393
62	764	814	1589	773	-50	817	20	28	743	932	-189
63	866	870	1965	882	-4*	1.083	27	28*	993	998	-5
64	698	714	983	681	-16	303	20	24*	730	723	7
65	755	749	1097	904	6*	193	19	14*	937	928	9
66	771	849	1145	1174	-78	-29	14	12*	1053	1050	3
67	823	818	1560	769	5*	791	23	28*	900	892	8
68	799	813	1372	762	-14	610	24	28	809	940	-131
69	729	721	1284	758	8*	526	22	22*	821	813	8
70	723	736	1175	738	-13	437	26	26*	843	846	-3
71	677	786	1211	742	-109	469	26	26*	925	932	-7
72	1019	1109	1400	1601	-90	-201	28	12	759	731	28

73	692	712	1593	699	-20	894	23	24*	718	713	5
74	618	716	1213	671	-99	542	21	26*	658	649	9
75	833	877	1578	887	-45	691	25	26	1016	946	70
76	707	719	1305	748	-12	557	24	28*	742	739	3
77	659	729	1345	671	-70	674	27	24*	882	880	2
78	954	1127	2139	1080	-173	1.060	27	28*	1295	1289	6
79	642	700	1120	665	-58	455	17	26	668	737	-69
80	648	686	1553	676	-38	878	27	28	748	952	-204
81	677	687	1965	682	-11	1.283	26	28	768	815	-47
82	660	648	1083	696	13	387	26	26*	756	748	8
83	753	786	1272	757	-33	515	22	28	837	858	-21
84	889	860	1651	914	29	738	22	28	892	912	-20
85	592	608	978	643	-17	335	21	22*	612	612	0
86	685	700	1469	732	-15	737	28	26	1320	894	426
87	832	845	1222	1507	-13	-285	15	10	903	884	19
88	643	663	1128	703	-20	425	18	20	675	689	-14
89	660	678	1142	698	-18	444	22	24	782	718	64
90	725	698	1521	719	27	803	21	28	766	829	-63
91	679	715	1387	663	-36	725	19	24	769	996	-227
92	681	701	1377	697	-21	681	28	28	698	869	-171
93	728	758	1503	755	-30	748	14	24	743	798	-55
94	572	571	1040	633	1*	407	23	22*	747	738	9
95	611	606	1284	609	5*	675	27	26*	743	744	-1
96	773	857	1433	835	-85	598	18	24	699	1049	-350
97	737	677	1253	731	60	522	25	26	917	776	141
98	672	716	1167	741	-44	426	23	28	801	1027	-226
99	738	723	1611	751	15	860	22	28	742	898	-156
100	644	686	1416	679	-42	737	26	28	797	844	-47
101	754	754	1161	822	0*	340	25	22*	841	836	5
102	703	741	1302	836	-38	466	26	20*	913	903	10
103	721	779	1127	1008	-58	119	19	16	741	872	-131
104	735	747	1178	734	-12	444	24	26	918	830	88
105	684	760	1174	678	-76	496	28	28	689	902	-213
106	729	751	1376	707	-22	669	24	28	649	770	-121
107	703	713	1428	694	-10*	734	21	26*	675	683	-8
108	757	752	1399	791	5*	608	27	26*	799	793	6
109	570	615	1194	576	-46	618	25	28	563	696	-133
110	613	690	1163	676	-77	487	23	24*	813	806	7
111	822	831	1335	765	-9*	570	26	26*	863	865	-2
112	780	761	1860	771	19	1.089	22	28*	982	978	4
113	570	627	973	692	-57	282	19	20*	682	692	-10
114	637	662	1102	726	-25	376	22	20	660	628	32
115	572	605	1179	573	-33	606	20	26	639	568	71
116	797	800	1233	858	-4*	375	25	24*	837	832	5
117	707	734	1205	812	-27	393	24	24*	875	870	5
118	591	606	986	593	-15	393	20	28*	586	595	-9
119	922	1034	1276	1258	-113	18	10	14	960	1014	-54
120	813	884	2030	874	-71	1.156	24	28	1013	1429	-416
121	753	720	1445	740	33	705	28	26	639	718	-79
122	917	899	2295	871	18	1.424	24	26	796	1286	-490
123	612	637	1362	629	-25	733	26	28*	755	750	5
124	749	740	1499	740	9*	759	26	26	886	840	46
125	680	686	1360	657	-6*	704	22	28	660	797	-137
126	747	762	1422	731	-15	691	28	28*	849	845	4
127	764	746	1770	720	18	1.051	25	28*	901	895	6
Mean	736	759	1377	793	-23	584	22	24	848	894	-46

Abbreviations: diff., differential variables; PR, Proximity conditions; LU, Luminance Similarity conditions.

Due to the heterogeneity of the information collected and the large number of participants, we decided to carry out two additional separate analyses, by distributing the participants according to their performance in the objective equating task, as well as, their performance in the single conditions of RDT.

4.2.2.3.1. Sub-groups analysis based on Objective Equating Task (OET)

Based on the objective equating task, we formed a sub-sample of fifty-six participants who managed to equal both principles, another sub-sample of sixteen participants who responded faster to proximity cues and, and finally, a third sub-sample of fifty-five participants who responded faster to luminance similarity cues. Firstly, we conducted a mixed ANOVA based on median RTs of correct responses. Stimulus type and Grouping cue were the target referred to within-subject's factors whereas Group was the between-subject's factor. Analyses on RTs showed a significant main effect of grouping cue, $F(1,124)= 262.4$, MSE= 6034360, $p < 0.001$, $\eta_p^2=.68$, pointing out that RTs for luminance cues were shorter (796 ms) than those for proximity cues (1053 ms). The main effect of Stimulus type was also significant, $F(1, 124)=858$, MSE= 10027254, $p < 0.001$, $\eta_p^2=.87$, indicating that single grouping cues yield faster responses (758 ms) than competing grouping displays (1090 ms). The interaction between the two factors was also significant $F(1, 124)= 359.7$, MSE= 7306615, $p < 0.001$, $\eta_p^2=.74$, showing that the interference effect of luminance cues on the response of targets grouped by proximity, the difference between competing and single displays, was greater (∆ 614 ms: 1360-746 ms) than the interference of proximity cues on the discrimination of stimuli grouped by luminance (∆ 49 ms: 820-771 ms). The post-hoc tests also showed that there is greater difference between both competing conditions (∆ 540 ms: 1360-820 ms) with each other compared to both single conditions to each other (∆ 25 ms: 746-771 ms). The difference between the conditions of proximity and luminance similarity single displays could justify the difference found between the conditions in competition. The three-way interaction between grouping cue, Stimulus type and Group was significant, $F(2, 124)= 5.7$, $MSE= 115277$, $p < 0.001$, $\eta_p^2=.84$. Pair-wise comparisons applying the Bonferroni correction showed significant differences between all pairs from the experimental conditions ($ps < 0.001$) except in the group conformed by fifty-six participants who managed to equal both principles and fifty-five participants, who respond faster to luminance cues. In concrete, we found significant differences when participants responded to luminance similarity single cues in comparison to luminance similarity competing cues, while between competing proximity and single proximity cues, we did not find any significant differences. Finally, we did not find significant results concerning between-subject's factors ($p > 0.001$).

With the aim of carrying out a more exhaustive inspection of our data we decided to perform three additional ANOVAs, one for each sub-group, the Stimulus type and Grouping cue were the target referred to within-subject's factors.

4.2.2.3.1.1.Fifty-six participants group analysis (OET)

In this case, the group that managed to match the times between the two factors consisted of fifty-six participants and the analyses on RTs showed a significant main effect of Stimulus type , $F(1, 55)= 512.9$, MSE= 5526087, $p < 0.001$, η_p^2=.90, pointing out that RTs for single cues (745 ms) were shorter than those for competing (1059 ms). The main effect of Grouping cue was also significant, $F(1, 55)= 227.1$, MSE= 3946657, $p < 0.001$, η_p^2=.80, indicating that luminance similarity grouping cues were respond faster (769 ms) than proximity grouping displays (1035 ms). Finally, the interaction between the two factors was significant $F(1, 55)= 287$, MSE= 4628462, $p < 0.001$, η_p^2=.84, showing that the interference effect of luminance similarity cues on the response of targets grouped by proximity, the difference between competing and single displays, was greater (∆ 602 ms: 1336-734 ms) than the interference of proximity cues on the discrimination of stimuli grouped by luminance similarity (∆ 18 ms: 783-756 ms).

4.2.2.3.1.2. Sixteen participants group analysis (OET)

The group that respond faster to the displays that contained the proximity grouping cues consisted of sixteen participants and the analyses on RTs showed a significant main effect of Stimulus type , $F(1,15)=174.4$, MSE= 1547847, $p < 0.001$, η_p^2=.92, pointing out that RTs for single cues (794 ms) were shorter than those for competing (1105 ms). The main effect of Grouping cue was also significant, $F(1, 15)= 19.8$, MSE= 526531.6, $p < 0.001$, η_p^2=.57, indicating that luminance similarity grouping cues were respond faster (859 ms) than proximity grouping displays (1040 ms). The interaction between the two factors was significant $F(1, 15)= 30.5$, MSE= 747576.4, $p < 0.001$, η_p^2=.67, showing that the interference effect of luminance similarity cues on the response of targets grouped by proximity, the difference between competing and single displays, was greater (∆ 527 ms: 1304-777 ms) than the interference of proximity cues on the discrimination of stimuli grouped by luminance similarity grouping cues (∆ 94 ms: 906-812 ms).

4.2.2.3.1.3. Fifty-five participants group analysis (OET)

Finally, the analyses on RTs of the group of fifty-five participants that respond faster to the displays that contained luminance similarity cues showed a significant main effect of Stimulus type , $F(1,54)=558.5$, MSE= 7482952.1, $p < 0.001$, $\eta_p^2=.91$, pointing out that RTs for single cues (736 ms) were shorter than those for competing (1104 ms). The main effect of Grouping cue was also significant, $F(1, 54)= 208.6$, MSE= 5782107, $p < 0.001$, $\eta_p^2=.78$, indicating that luminance similarity grouping cues were respond faster (758 ms) than proximity grouping displays (1082 ms). The interaction between the two factors was significant $F(1, 54)= 279.4$, MSE= 6541545.8, $p < 0.001$, $\eta_p^2=.84$, showing that the interference effect of luminance similarity cues on the response of targets grouped by proximity, the difference between competing and single displays, was greater (∆ 713 ms: 1439-726 ms) than the interference of proximity cues on the discrimination of stimuli grouped by luminance similarity cues (∆ 24 ms: 770-746 ms).

4.2.2.3.2.Sub-groups analysis based on Repetition Discrimination Task (RDT)

We selected another three different sub-samples of participants based on the differential variable obtained from the RDT task (as a result of subtracting the mean RT from single proximity cues from the mean RT of single luminance similarity cues obtained in the RDT for each participant). Hence, the sub-sample that included participants who responded faster to single proximity cues in the RDT consisted of twenty-three. Seventy-eight participants were included in the luminance similarity sub-sample and the twenty-six participants who reached a difference lesser or equal than 10 ms between single conditions from the RDT were included in the third sub-sample. As we did above, we performed a mixed ANOVA based on median RTs of correct responses including the same factors, only changing the composition of the group. Analyses on RTs showed a significant main effect of grouping cue, $F(1,124)= 465$, MSE= 9511141.7, $p < 0.001$, $\eta_p^2=.79$, pointing out that RTs for proximity cues (1087 ms) were larger than those for luminance similarity (770 ms). Also, a main effect of Stimulus type , $F(1,124)= 1096.9$, MSE= 11850233.6, $p < 0.001$, $\eta_p^2=.89$, indicating that single grouping cues were respond faster (752 ms) than competing grouping displays (1105 ms). The interaction between the two factors was significant $F(1,124)= 477.2$, MSE= 9846989.2, $p < 0.001$, $\eta_p^2=.79$, showing that the interference effect of luminance similarity cues on the response of targets grouped by proximity was greater (Δ 676 ms: 1425- 749 ms) than the interference of proximity cues on the discrimination of stimuli grouped by luminance similarity (Δ 31 ms: 786-755 ms). The post-hoc tests also showed that there is greater difference between both competing conditions (Δ 639 ms: 1425-786 ms) with each other compared to both single conditions to each other (Δ 6 ms: 749-755 ms). The difference between the conditions of proximity and luminance similarity single displays could justify the difference found between the conditions in competition. The three-way interaction between grouping cues, Stimulus type and Group, did not reach significant levels ($p > 0.001$). However, we find significant results concerning between-subject's factors ($p < 0.001$). In fact, the differences only occur between groups between the group that managed to match the two principles (896 ms) and the one that responded the fastest to the grouping by luminance similarity (901 ms) ($p = 0.044$) with respect to the final average of all the conditions of the RDT, but the pattern of results is the same in all groups independently of this finding.

As on previous occasions, we performed three additional ANOVAs, one for each sub-group, the Stimulus type and Grouping cue were the target referred to within-subject's factors.

4.2.2.3.2.1. Twenty-six participants group analysis (RDT)

In this case, the group that managed to match the times between the two factors consisted of twenty-six participants and the analyses on RTs showed a significant main effect of Stimulus type, $F(1,25)=311.2$, MSE= 2630178 , $p < 0.001$, $\eta_p^2=.92$, pointing out that RTs for single cues (736 ms) were shorter than those for competing (1054 ms). The main effect of Grouping cue was also significant, $F(1, 25)= 222$, MSE= 2367379.6, $p < 0.001$, $\eta_p^2=.90$, indicating that luminance similarity grouping cues were respond faster (745 ms) than proximity grouping displays (1046 ms). The interaction between the two factors was significant $F(1, 25)= 220$, MSE= 2377650.2, $p < 0.001$, $\eta_p^2=.90$, showing that the interference effect of luminance similarity cues on the response of targets grouped by proximity, the difference between competing and single displays, was greater (Δ 621 ms: 1357- 736 ms) than the interference of proximity cues on the discrimination of stimuli grouped by luminance similarity(Δ 16 ms: 753- 737 ms).

4.2.2.3.2.2. Seventy-eight participants group analysis (RDT)

The group that respond faster to the displays that contained the luminance similarity cues consisted of seventy-eight participants, and the analyses on RTs showed a significant main effect of Stimulus type, $F(1,77)=755.6$, MSE= 7922053.4, $p < 0.001$,

η_p^2=.90, pointing out that RTs for single cues (742 ms) were shorter than those for competing (1060 ms). The main effect of Grouping cue was also significant, F(1, 77)= 193.4, MSE= 4265353.8, $p < 0.001$, η_p^2=.71, indicating that luminance similarity grouping cues were respond faster (784 ms) than proximity grouping displays (1018 ms). The interaction between the two factors was significant F(1, 77)= 278.2, MSE= 6116320, $p < 0.001$, η_p^2=.78, showing that the interference effect of luminance similarity cues on the response of targets grouped by proximity, the difference between competing and single displays, was greater (Δ 599 ms: 1318- 719 ms) than the interference of proximity cues on the discrimination of stimuli grouped by luminance similarity(Δ 39 ms: 804- 765 ms).

4.2.2.3.2.3. Twenty-three participants group analysis (RDT)

Finally, the analyses on RTs of the group of twenty-three participants that respond faster to the displays that contained proximity cues showed a significant main effect of Stimulus type, $F(1,22)$=281.9, MSE= 4114098, $p < 0.001$, η_p^2=.93, pointing out that RTs for single cues (777 ms) were shorter than those for competing (1200 ms). The main effect of Grouping cue was also significant, F(1, 22)= 67.8, MSE= 3937555.3, $p < 0.001$, η_p^2=.87, indicating that luminance similarity grouping cues were respond faster (782 ms) than proximity grouping displays (1196 ms). The interaction between the two factors was significant F(1, 22)= 124.9, MSE= 3383428.7, $p < 0.001$, η_p^2=.85, showing that the interference effect of luminance similarity cues on the response of targets grouped by proximity, the difference between competing and single displays, was greater (Δ 806 ms: 1599- 793 ms) than the interference of proximity cues on the discrimination of stimuli grouped by luminance similarity (Δ 35 ms: 802- 767 ms).

Thus, we found the same pattern of significant effects related to the complete sample previously analysed and described in the manuscript. This fact points out that independently of the performance in the previous phase's luminance similarity dominates over proximity cues finally in the RDT. We could observe again and with a considerable sample increase, that participants who equated both single cues in the objective equating task (fifty-six participants whose values were marked with an asterisk) were not necessarily the same participants who reached ±10 ms of difference between single conditions in the RDT task(twenty-six participants whose values were marked with an asterisk). For example, participant # 9 matched the reaction times between both cues in the objective equating task, while in the differential variable referred to the single conditions of the RDT this participant obtained a difference of 130 ms between both. On the other hand, as an example, the participant # 28, did not manage to match in the objective equating task the reaction times of both principles, but nevertheless this participant obtained in the differential variable of the single conditions of the RDT a difference less than 10 ms , specifically a difference of 5 ms between both. In Experiment 1, only four participants from a sample of one hundred twenty-seven participants, showed faster performance related to proximity competing displays in comparison with luminance competing cues. This fact reinforces the consistent pattern of results related to competing conditions, and again, claiming the dominance of luminance similarity cues, despite the heterogeneity in the results obtained.

Accuracy analysis. Hit rates ranged between 95% and 100%. ANOVA results reported a significant main effect for Grouping cue, $F(1,126) = 22.5$, $p < .001$, $\eta_p^2 = .151$, thus luminance displays were responded more accurately (.97) than those proximity targets (.96). Similarly, a significant main effect for Stimulus type, $F(1,126) = 33.1$, $p < .001$, $\eta_p^2 = .208$, thus single displays were responded more accurately (.97) than those competing targets (.96). Also, a significant interaction between Stimulus type and Grouping cue was found, $F(1,126) = 44.4$, $p < .001$, $\eta_p^2 =.261$. Pair-wise comparisons with the Bonferroni correction showed significant differences within the Stimulus type condition, specifically, between competing proximity (.95) and luminance similarity cues (.97), $p < .05$. Likewise, significant differences were found regarding Grouping cue conditions, between proximity single (.97) and proximity competing cues (.95), $p = .000$. The rest of the comparisons did not reach significant values, $p > .05$.

4.3. Experiment 2. Common region and Connectedness

4.3.1. Method

4.3.1.1. Participants

Fifty-two undergraduate students (14 men; age range: 19-60 years, M = 31.45, SD = 10.82) from the UNED participated in the study. All of them received course credits for their participation in the experiment and they had normal or corrected-to-normal vision. The experimental procedure was approved by the Local Ethics Committee and conforms to the Declaration of Helsinki.

4.3.1.2. Apparatus

The stimulus patterns were displayed on a 19-inch (c.48.25-cm) LCD-LED colour monitor with a 75-Hz refresh rate, a 5:4 aspect ratio, and a resolution of 1280 x 1024 pixels, controlled by a personal computer running E-Prime 2.0 software (Psychology Software Tools, 1996 – 2013). Viewing distance was nearly 60 cm. Responses were recorded using a standard keyboard.

4.3.1.3. Stimuli

The stimuli set was based on previous works by Palmer and Beck (2007) and Montoro et al (2017). The displays consisted of a row of nine dark (RGB: 0; 0.06 cd/m^2) equidistant elements that alternated between squares and circles, which subtended 9 x 9 mm (0.86º v.a.). The entire array of nine elements had 152 mm (14.22º v.a.) vertically. The edge-to-edge distance between elements was 9 mm (0.86º v.a.).

For the RDT phase, 48 different stimuli were drawn (Figure 3A): 24 displays for the single conditions and 24 for the competing conditions. The nine elements alternated between circles and squares, except for a single pair of adjacent similar shapes. In the common region-only condition, four light grey (RGB: 128; 14.1 cd/m^2) connectors (vertical length: 9 mm; 0.86º v.a.) were added as connectedness cues. The thickness value of the connectors was adapted for every single participant and based on the results of the objective equating phase (see *Results* section). In the competing conditions, both ovals and connectors were included as a part of the stimuli.

In the objective equating phase, the stimuli were the same 24 patterns displayed in the RDT phase for the single conditions (Figure 3B). The thickness values assigned to single connectedness were adapted for every single participant and taken from the scaling task, which was performed previously to this phase.

In the scaling task, all of stimuli were competing patterns which alternated square/circle shapes in absence of target pairs (Figure 3A). Thirty different stimuli were designed by manipulating the thickness value of the connectors from 1 to 30 pixels by one-unit increment (pixels 1 to 30).

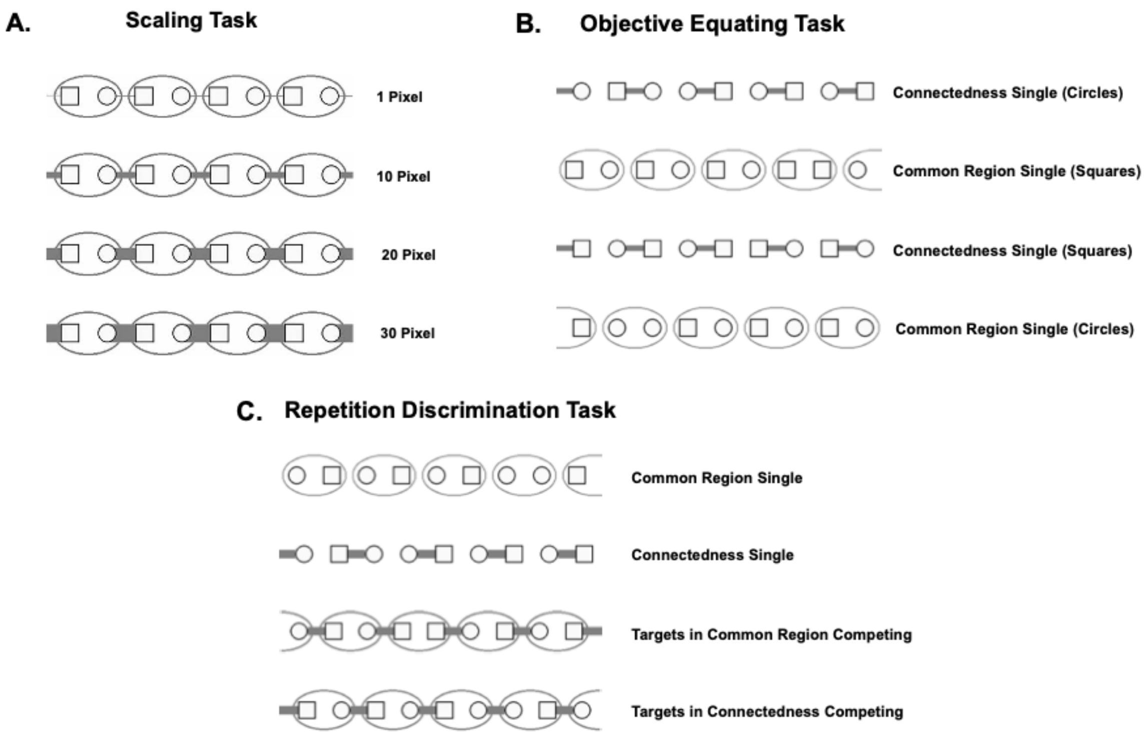


Figure 3. Examples of stimuli displayed in the Scaling Task **(A),** Objective Equating Task **(B)** and Repetition Discrimination Task **(C)** . The thickness of the connectors is equal to 10 pixels related to the Objective Equating Task and 15 pixels to Repetition Discrimination Task.

4.3.1.4. Design and procedure

The 2x2 design included two within-subject factors: Stimulus type *(single or competing grouping cues)* and Grouping cue *(common region or connectedness)*. These four different types of stimuli were combined with six different positions of the target pair (elements 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, counting from the left), two shapes of the target pairs (circles vs. squares) and two repetitions in order to obtain a total number of 96 trials for each experimental block. Dependent variables measured were reaction times (RTs) and error rates (ACC).

Participants were individually tested in a quiet room in three different phases: (1) scaling task, (2) objective equating task and (3) RDT. In the scaling task, participants had to manipulate the thickness of the connectors which joined the geometric elements until their grouping strength (i.e. connectedness) seemed as equally strong as the grouping strength of the common region cue, therefore producing a grouped pair of elements of equal salience in figures joined together by connectors and in figures included in ovals. Due to the nature of the task, the instructions emphasized that judgments should be based on the grouping strength or subjective salience of the extrinsic cues and not on the physical attributes (i.e thickness of the inductors) of each cue. Participants performed one practice trial and six scaling trials: three trials starting with 1 pixel in thickness (i.e. *ascending* trials) and the other three beginning with 30 pixels in thickness (i.e. *descending* trials). The order of presentation of the trials was counterbalanced between subjects. Participants manipulated the values of the connectors by pressing the right (to increase the thickness) or left arrow (to decrease the thickness) keys of the keyboard with the index fingers of both hands. There was no time limit. When they were sure of their decision, they verbally confirmed their final choice, and left the screen static so that the experimenters could record the specific value of thickness. Participants were not informed about the value of the thickness' connector. Taking the six values recorded, an average value was calculated for each participant. The mean value was implemented as the thickness value of the connectors in the stimuli displayed in the subsequent objective equating task.

In the objective equating task, the thickness value of the scaling phase was used as the starting criterion and participants were required to indicate the shape of the repeated pair of elements (circle or square), as fast as possible while avoiding errors, by pressing one of two keys (“Z” and “M”, respectively) using their left or right index. The stimulus array displayed on the centre of the screen remained until response. The inter-trial interval was 800 ms. In this phase, there were only two experimental conditions, single connectedness and single common region cues. In each block, the average value of correct RT trials for each experimental condition was obtained. When average RT differences between grouping cues were higher than 10 ms, the software added (or subtracted) a pixel to the connectors of the connectedness cue, depending on whether the participant responded slower (or faster) to connectedness cue compared to common region. When average RT differences between conditions were less than or equal to 10 ms, it was assumed that both principles were equated at the visuomotor level. In this case, the pixel thickness value was recorded and later used for the RDT phase. Participants could perform up to 10 experimental blocks, with a total of 480 experimental trials (240 trials for single common region and 240 for single connectedness cues). There was a practice block with 24 trials and feedback was provided only for those practice trials. If after the 10 experimental blocks, the average RT differences between grouping cues were not less than or equal to 10 ms, the thickness value of the last block was used for the RDT phase.

Finally, in the RDT, the thickness value of the connector was taken from the objective equating task. Instructions (see Appendix II) were the same as the previous phase *(objective equating task)*. In this phase, there were four experimental conditions, namely: two single conditions (one displaying common region cues and another one with connectedness) and two competing conditions (one with targets grouped by common region and another one with targets grouped by connectedness). The stimulus array was displayed on the centre of the screen and it remained until response. The inter-trial interval was 800 ms. There was a practice block with 48 trials, where feedback was provided, and six experimental blocks of 96 trials each, for a total of 576 experimental trials.

4.3.2. Results and discussion

4.3.2.1. Scaling task

Mean pixel adjusted values varied between 2 and 25 (mean = 9; SD= 6). Data showed a great variability among participants' judgments in their perception of relative grouping strength.

4.3.2.2. Objective equating task

In this phase, final pixel values were found in the range of 0 and 30 pixels (mean = 14.25; SD= 8.7). After the 10 experimental blocks, 10 of the 52 participants equated the grouping strengths of the different cues, whereas 42 participants did not reach a RT difference of 10 ms or less between grouping cues.

4.3.2.3. Repetition discrimination task

Median RTs of correct responses and mean accuracy rates were submitted to separate analyses of variance (ANOVAs) with Stimulus type and Grouping cue as within-subject's factors.

RT analysis. RTs less than 200 ms and greater than 4000 ms (172 of 29078; 0.59 % of trials) and inaccurate responses (874 of 29952; 2.9 % of trials) were not included in the RT analyses.

Analyses of RTs showed a significant main effect of Grouping cue, $F(1,51) = 360$, $MSE = 6363351$, $p < .001$, $\eta_p^2 = .876$, pointing out that RTs for common region cues (757 ms) were shorter than those for connectedness (1107 ms). The main effect of Stimulus type was significant, $F(1,51) = 534.4$, $MSE = 7656580$, $p < .001$, $\eta_p^2 = .913$, indicating that single grouping cues were responded faster (740 ms) than competing grouping displays (1124 ms).

Lastly, the interaction between the two factors was significant $F(1,51) = 285.7$, $MSE = 4908626$, $p < .001$, $\eta_p^2 = .849$, showing that the interference effect (measured as the difference between competing and single conditions) of common region on connectedness was significantly greater (Δ691 ms: 1452 - 761 ms) than vice versa (Δ77 ms: 795 - 718 ms). Pair-wise comparisons making use of Bonferroni correction displayed significant differences between all pairs from the experimental conditions (all of them *ps* $\leq .001$).

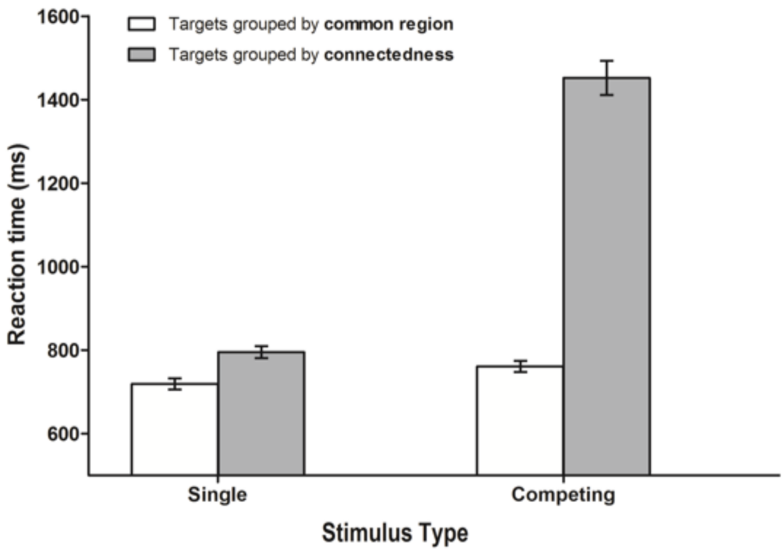


Figure 4. Mean reaction times (ms) and standard error bars for the experimental conditions of the RDT.

Our results replicated those by Montoro et al. (2017), despite the fact of introducing a prior objective equating task. In order to further explore the relationship between the repetition discrimination task (RDT), the scaling task and the objective equating task, we introduce a table **(Table 2)** that collects individual performance.

Table 2. Individual responses and mean values to the RDT, scaling task and objective equating task. Differential variables to the RDT and objective equating task.

	Single conditions		Competing conditions								
Subject	**CN**	**CR**	**CN**	**CR**	**Diff. Singles RDT CN-CR**	**Diff. Competing RDT CN-CR**	**Scaling task mean values**	**Objective Equating task mean values**	**Objective Equating CN**	**Objective Equating CR**	**Diff. Objective Equating CN-CR**
1	965	936	2310	985	29	1325	3	3*	1217	1209	8
2	724	613	1438	711	111	727	11	20	799	756	43
3	746	714	1087	782	32	305	25	30	832	730	102
4	737	685	1117	786	52	332	2	11	881	803	78
5	914	853	2342	890	61	1452	6	15	1020	942	78
6	756	746	1435	761	10*	674	4	1	795	829	-34
7	749	767	1659	793	-18	866	4	13	833	812	21
8	773	757	1613	850	16	763	7	4*	967	958	9
9	738	662	1443	739	76	704	11	20	843	741	102
10	912	812	1854	813	100	1042	5	14	982	910	72
11	745	766	1338	809	-21	529	3	2*	865	867	-2
12	678	659	1391	728	19	664	10	17	811	719	92
13	768	710	1772	817	58	955	14	14*	944	954	-10
14	822	750	1395	798	73	598	2	11	865	812	53
15	848	702	1533	891	146	642	8	17	1058	970	88
16	689	655	1442	726	34	716	18	27	868	803	65
17	730	773	1336	816	-43	520	2	1	853	1047	-194
18	916	894	1604	955	23	649	4	13	1200	1080	120
19	871	906	1785	920	-35	865	2	1	1023	1120	-97
20	869	809	1484	901	60	583	20	26*	945	936	9
21	759	689	1690	823	70	867	8	17	894	791	103
22	679	643	1188	712	36	476	4	13	826	773	53
23	665	648	1264	715	17	550	4	1	828	896	-68
24	718	661	1194	768	57	426	3	12	836	769	67
25	759	676	1201	1014	84	187	22	30	951	862	89
26	641	588	1097	626	54	472	4	13	754	722	32
27	757	702	1272	850	55	422	17	26	968	862	106
28	593	607	1047	606	-14	441	11	20	810	795	15
29	790	796	1564	823	-7*	742	3	10	933	881	52
30	754	694	1216	741	61	475	3	12	938	846	92
31	836	732	1497	827	104	671	6	15	1210	883	327
32	1014	926	2005	1057	88	948	9	16*	1194	1194	0
33	675	634	1381	648	41	733	10	9*	768	770	-2
34	856	770	1368	837	86	531	16	25	1071	998	73
35	625	569	1267	608	56	660	11	20	759	654	105
36	791	748	1283	837	43	446	5	14	899	847	52
37	813	777	2008	863	36	1146	9	14	967	906	61
38	854	763	1478	933	92	546	12	21	938	909	29

39	726	717	1162	808	9*	354	10	17	883	862	21
40	668	690	1709	750	-22	959	13	4	790	826	-36
41	720	724	1276	776	-5*	500	5	1	807	842	-35
42	917	839	1479	908	78	571	8	8*	960	963	-3
43	806	811	1783	829	-6*	954	5	10	1150	978	172
44	620	642	1235	666	-22	569	3	1	830	884	-54
45	683	675	1327	774	9*	553	20	27	779	757	22
46	694	612	1469	673	82	796	9	18	778	724	54
47	758	735	1510	763	23	747	2	3*	883	892	-9
48	774	714	1584	738	60	846	9	10*	822	815	7
49	593	565	989	604	28	385	19	28	659	616	43
50	793	628	1580	792	165	788	16	25	935	890	45
51	661	650	986	660	11	327	10	19	775	683	92
52	653	588	1037	859	65	178	19	28	729	667	62
Mean	**761**	**719**	**1452**	**795**	**43**	**657**	**9**	**14**	**902**	**861**	**42**

Abbreviations: diff., differential variables; CN, Connectedness conditions; CR, common region conditions.

Noteworthy, in the objective equating phase, eight participants did not complete all the blocks, although they did not show similar RTs to both grouping cues: six of them obtained the value of 0 pixels (and in the RDT phase, they were assigned the thickness value of 1 pixel) and two of them reached the maximum value (i.e. 30 pixels), ten participants were able to respond with a difference of ± 10 ms with respect to each of the principles arranged on the screen. The remaining 34 participants performed the maximum number of ten blocks and the thickness value used in their RDT was the last value from the block number 10.

Due to the heterogeneity of the information collected and the large number of participants, we decided to carry out two additional separate analyses by distributing the participants according to their performance in the objective equating task, as well as, their performance in the RDT.

4.3.2.3.1. Sub-groups analysis based on Objective Equating Task (OET)

Based on the results from the objective equating task, we formed a sub-sample of ten participants who managed to equal both principles, another sub-sample of seven participants who responded faster to connectedness cues and, finally, a third sub-sample of thirty-five participants who responded faster to common region cues. Firstly, we conducted a mixed ANOVA based on median RTs of correct responses. Stimulus type and Grouping cue were the target referred to within-subject's factors whereas group was the between-subject's factor. Analyses on RTs showed a significant main effect of grouping cue, $F(1,49)= 251.6$, MSE= 4297860, $p < 0.001$, $\eta_p^2=.84$, pointing out that RTs for common region cues (769 ms) were shorter than those for connectedness (1129 ms). The main effect of Stimulus type was also significant, $F(1, 49)= 371.9$, MSE= 5206474.7, $p < 0.001$, $\eta_p^2=.88$, indicating that single grouping cues yield faster responses (751 ms) than competing grouping displays (1148 ms). The interaction between the two factors was significant $F(1, 49)= 226.1$, MSE= 3664683.8, $p < 0.001$, $\eta_p^2=.82$, showing that the interference effect of common region cues on the response of targets grouped by connectedness, the difference between competing and single displays, was greater (Δ 729 ms: 1494-765 ms) than the interference of connectedness cues on the discrimination of stimuli grouped by common region (Δ ms: 801-738 ms). The post-hoc tests also showed that there is greater difference between both competing conditions (Δ 693 ms: 1494-801 ms) with each other compared to both single conditions to each other (Δ 27 ms: 765-738 ms). The difference between the conditions of common region and connectedness single displays could justify the difference found between the conditions in competition. Finally, we found significant results concerning between-subject's factors ($p < 0.001$). However, the three-way interaction between Stimulus type, Grouping cue and Group was not significant ($p = 0.09$) so we assume that the performance pattern between groups was similar. Similarly, in order to carry out an exhaustive analysis of the data patterns of each subgroup, a separate analysis was carried out, since although it was not significant, there was a marginal difference of the three-way interaction ($p = 0.09$).

In order to conduct a deeper analysis of these data, we conducted three additional ANOVAs, one for each sub-group, and again Stimulus type and Grouping cue were the target referred to within-subject's factors.

4.3.2.3.1.1. Ten participants group analysis (OET)

With respect to the group formed by ten participants that were able to equal both principles, analyses on RTs showed a significant main effect of Stimulus type , $F(1,9)=124.9$, MSE= 1966257.3, $p < 0.001$, $\eta_p^2=.93$, pointing out that RTs for single cues (804 ms) were shorter than those for competing (1247 ms). The main effect of Grouping cue was also significant, $F(1, 9)= 119.6$, MSE= 1776833.2, $p < 0.001$, $\eta_p^2=.93$, indicating that common region grouping cues showed faster responses (815 ms) than connectedness grouping displays (1236 ms). The interaction between both factors was significant, $F(1, 9)= 104.2$, MSE= 1432054.8, $p < 0.001$, $\eta_p^2=.92$, showing that the interference effect of common region cues on the response of targets grouped by connectedness, the difference between competing and single displays, was greater (Δ 822 ms: 1648-826 ms) than the interference of connectedness cues on the discrimination of stimuli grouped by common region (Δ 65 ms: 848-783 ms)

4.3.2.3.1.2. Thirty-five participants group analysis (OET)

The analyses on RTs of the group formed by thirty-five participants that responded faster to the targets formed by common region, showed a significant main effect of Stimulus type, $F(1,34)=327.2$, MSE= 4737816.2, $p < 0.001$, $\eta_p^2=.91$, pointing out that RTs for single cues (724 ms) were shorter than those for competing (1092 ms). The main effect of Grouping cue was also significant, $F(1, 34)= 202.8$, MSE= 3915657, $p < 0.001$, $\eta_p^2=.86$, indicating that common region grouping cues are responded faster (741 ms) than connectedness grouping displays (1076 ms). The interaction between the both was significant, $F(1, 34)= 151.9$, MSE= 2757877.5, $p < 0.001$, $\eta_p^2=.82$, showing that the interference effect of common region cues on the response of targets grouped by connectedness, the difference between competing and single displays, was greater (Δ 649 ms: 1400-751 ms)than the interference of connectedness cues on the discrimination of stimuli grouped by common region (Δ 87 ms: 785-698 ms).

4.3.2.3.1.3. Seven participants group analysis (OET)

Lastly, the analyses on RTs of the seven participants belonging to the group that responded faster to the displays formed by connectedness showed a significant main effect of Stimulus type, $F(1,6)=114.9$, MSE= 997166.3, $p < 0.001$, $\eta_p^2=.95$, pointing out that RTs for single cues (725 ms) were shorter than those for competing (1103 ms). The main effect of Grouping cue was also significant, $F(1, 6)= 93.9$, MSE= 735156, $p < 0.001$, $\eta_p^2=.94$, indicating that common region grouping cues are responded faster (752 ms) than connectedness grouping displays (1076 ms). The interaction between both factors was significant $F(1, 6)= 90.1$, MSE= 800722.3, $p < 0.001$, $\eta_p^2=.94$, showing that the interference effect of common region cues on the response of targets grouped by connectedness, the difference between competing and single displays, was greater (Δ 716 ms: 1434-719 ms) than the interference of connectedness cues on the discrimination of stimuli grouped by common region (Δ 39 ms: 772-733 ms).

Despite conducting these complementary analyses categorized by groups based on their performance, the pattern of data found was common in all subgroups.

4.3.2.3.2. Sub-groups analysis based on Repetition Discrimination Task (RDT)

We selected another three different sub-samples of participants based on a differential variable computed from the RDT task (as a result of subtracting the mean RT from single connectedness cues from the mean RT of single common region cues obtained in the RDT for each participant; see Table 2). Hence, the sub-sample that included participants who responded faster to single common region cues in the RDT consisted of thirty-nine participants. Seven participants were included in the connectedness sub-sample and the six participants who reached a difference lesser or equal than 10 ms between single conditions from the RDT were included in the third sub-sample. As we did above, we performed a mixed ANOVA based on median RTs of correct responses including the same factors, only changing the composition of the group. Analyses on RTs showed a significant main effect of Grouping cue, $F(1,49)= 165.3$, MSE= 2992487.5, $p < 0.001$, $\eta_p^2=.77$, pointing out that RTs for common region cues (759 ms) were shorter than those for connectedness (1093 ms). Also, a main effect of Stimulus type , $F(1,49)= 257.7$, MSE= 3828277.2, $p < 0.001$, $\eta_p^2=.84$, indicating that single grouping cues were respond faster (737 ms) than competing grouping displays (1114 ms). The interaction between the two factors was significant $F(1,49)= 158$, MSE= 2770136.2, $p < 0.001$, $\eta_p^2=.76$, showing that the interference effect of common region cues on the response of targets grouped by connectedness was greater(Δ 699 ms: 1442-743 ms) than the interference of connectedness cues on the discrimination of stimuli grouped by common region (Δ 56 ms: 787-731 ms). The post-hoc tests also showed that there is greater difference between both competing conditions (Δ 655 ms: 1442-787 ms) with each other compared to both single conditions to each other (Δ 12 ms: 743-731 ms). The difference between the conditions of common region and connectedness single displays could justify the difference found between the conditions in competition. However, we did not find any significant results concerning between-subject's factors ($ps > 0.001$).

As in the previous phase, we performed three additional ANOVAs, one for each sub-group, in order to exhaustively explore the pattern of results in each sub-sample, and the Stimulus type and Grouping cue were the target referred to within-subject's factors.

4.3.2.3.2. 1. Six participants group analysis (RDT)

In this case, the group that matched the TRs between the two factors consisted of six participants, and the analyses on RTs showed a significant main effect of Stimulus type , $F(1,5)=119.3$, MSE= 794976, $p < 0.001$, $\eta_p^2=.96$, pointing out that RTs for single cues (746 ms) were shorter than those for competing (1110 ms). The main effect of Grouping cue was also significant, $F(1, 5)= 56.9$, MSE= 597241.5, $p < 0.001$, $\eta_p^2=.92$, indicating that common region grouping cues were respond faster (770 ms) than connectedness grouping displays (1085 ms). The interaction between the two factors was significant $F(1, 5)= 51.9$, MSE= 590320.7, $p < 0.001$, $\eta_p^2=.91$, showing that the interference effect of common region cues on the response of targets grouped by connectedness, the difference between competing and single displays, was greater (Δ 678 ms: 1424-746 ms) than the interference of connectedness cues on the discrimination of stimuli grouped by common region (Δ 50 ms: 795-745 ms).

4.3.2.3.2. 2. Thirty-nine participants group analysis (RDT)

The group with faster responses to common region cues consisted of thirty-nine participants, and the analyses on RTs showed a significant main effect of Stimulus type, $F(1,38)=360.3$, MSE= 5845055.2, $p < 0.001$, $\eta_p^2=.90$, pointing out that RTs for single cues (742 ms) were shorter than those for competing (1129 ms). The main effect of Grouping cue was also significant, $F(1, 38)= 248.9$, MSE= 5033002.7, $p < 0.001$, $\eta_p^2=.87$, indicating that common region grouping cues were respond faster (756 ms) than connectedness grouping displays (1115 ms). The interaction between the two factors was significant $F(1, 38)= 179.2$, MSE= 3470064.2, $p < 0.001$, $\eta_p^2=.82$, showing that the interference effect of common region cues on the response of targets grouped by connectedness, the difference between competing and single displays, was greater (Δ 685 ms: 1458-773 ms) than the interference of connectedness cues on the discrimination of stimuli grouped by common region (Δ 88 ms: 800-712 ms).

4.3.2.3.2. 3. Seven participants group analysis (RDT)

Finally, the analyses on RTs of the group of seven participants that respond the fastest to the displays that contained connectedness cues showed a significant main effect of Stimulus type, $F(1,6)=78.4$, MSE= 1019368.1, $p < 0.001$, $\eta_p^2=.93$, pointing out that RTs for single cues (723 ms) were shorter than those for competing (1105 ms). The main effect of Grouping cue was also significant, $F(1, 6)= 67.8$, MSE= 747358.9, $p < 0.001$, $\eta_p^2=.92$, indicating that common region grouping cues were respond faster (750 ms) than connectedness grouping displays (1077 ms). The interaction between the two factors was significant $F(1, 6)= 78.3$, MSE= 865393.1, $p < 0.001$, $\eta_p^2=.93$, showing that the interference effect of common region cues on the response of targets grouped by connectedness, the difference between competing and single displays, was greater (Δ 733 ms: 1444-711 ms) than the interference of connectedness cues on the discrimination of stimuli grouped by common region (Δ 30 ms: 766-736 ms).

Interestingly, we found the same pattern of results as the complete sample previously analysed. This fact points out that independently of the performance in the previous phases (subjective and objective equating tasks), common region gains dominance over element connectedness. We could observe that participants who equated both single cues in the objective equating task (#1, #8, #11, #13, #20, #32, #33, #42, #47, #48) were not necessarily the same participants who reached ±10 ms of difference between single conditions in the RDT task (#6, #29, # 39, #41, #43, #45). Remarkably, not a single participant showed faster performance related to connectedness competing displays in comparison with common region competing cues. This fact reinforces the consistent pattern of results related to competing conditions, and again, supports the dominance of common region cues.

Accuracy analysis. Hit rates ranged between 96% and 100%. ANOVA results reported a significant main effect for Stimulus type, $F(1,51) = 12.45$, $p < .005$, $\eta_p^2 = .196$, thus single displays were responded more accurately (.97) than those competing targets (.96). Also, a significant interaction between Stimulus type and Grouping cue was found, $F(1,51) = 18.25$, $p < .001$, $\eta_p^2 =.264$. Pair-wise comparisons with the Bonferroni correction showed significant differences within the Stimulus type condition, specifically, between common region competing (.97) and connectedness competing cues (.96), $p < .05$. Likewise, significant differences were found regarding Grouping cue conditions, between connectedness single (.98) and connectedness competing cues (.96), $p = .000$. The rest of the comparisons did not reach significant values, $p > .05$.

4.4. General Discussion

Recent studies on competition between different visual grouping cues (e.g., Luna et al., 2016; Montoro et al., 2017; Schmidt & Schmidt, 2013) corroborate that a prior adjustment of grouping strength of these cues based on subjective measures does not guarantee necessarily that these grouping factors have an equivalent representation in the visuomotor system. The present study goes beyond past work by introducing a novel objective equating procedure that intends to provide a complementary matching of grouping strength of these cues in visuomotor system prior to performance experimental tasks. To achieve this goal, we examined competition dynamics between two intrinsic grouping cues -proximity and luminance similarity (Exp.1)- and two extrinsic grouping cues -common region and element connectedness (Exp. 2)- in a *repetition discrimination task* (RDT), which provides an indirect measure of interactions between multiple grouping cues (Montoro et al., 2017; Palmer & Beck, 2007). Crucially, we introduced two sequential phases (i.e. *subjective* and *objective* equating tasks) before both cues competed for visual organization in the same stimulus pattern (i.e. RDT phase).

As we expected, results from Exp. 1 showed that single grouping cues were responded faster than competing grouping displays. Moreover, participants responded faster when two consecutive repeated elements shared same luminance values (luminance similarity competing conditions) than when both repeated elements are close to each other (proximity competing conditions). Of note, luminance similarity interference exerted on proximity cues in competing displays was greater than proximity interference over luminance cues. Thus, we found a bidirectional but asymmetric interference effect. Although all observers performed the objective equating task, not all managed to obtain a difference of ± 10 ms in RTs between proximity and luminance similarity single cues. Specifically, only fifty-six participants did it. In the same way, we conducted several analysis by different sub-groups, and even in that fifty-six group of participants whose RTs were similar between both single conditions (objective equating task), in RDT their RTs showed large differences between conditions. We found same performance in RDT throughout the complete sample of participants. Still, there are prior studies devoted to studying interactions between proximity and luminance similarity cues, some of these studies were based on phenomenological and / or direct measures (e.g., Ben-Av & Sagi, 1995; Hochberg & Silverstein, 1956; Kubovy & van den Berg, 2008; Quinlan & Wilton, 1998). Conversely, some of these studies only allude to additive effects of cooperation between cues, which has not been explored in our experiment (e.g., Hochberg & Silverstein, 1956). Other studies that explored interactions between both principles in direct competition (e.g., Ben-Av & Sagi, 1995) included manipulations, such as masks and SOAs, not controlled in our experiment. In fact, Ben-Av and Sagi (1995) found that depending on the SOA duration, one principle could dominate perceptual organization or another, neither unable to quantify the dominance magnitude. Quinlan and Wilton (1998) also studied interactions between proximity and luminance similarity, but again through a direct method involving phenomenological measures. Their results do not match those found in our experiment, as they found that proximity cues were dominant. However, they also affirmed that depending on how these cues interact, this dominance effect could be even neutralized by similarity cues. Kubovy and van den Berg (2008) studied relationships between these two intrinsic principles, eventually defining a function that predicts how grouping by proximity varies depending on relative distance of the grouped elements. In the same way, these authors found cooperative effects between both grouping factors, which they described as additives. Anyway, in these previous cited studies, operations and relationships between proximity and luminance similarity cues are not entirely clear in a unified way. Furthermore, divergences found between our data and previous literature, can be explained by these methodological details and more specifically, indirect measures have been used in our study. We only examined competition operations and more importantly in our study can be quantified the relative contribution of each single cue to the competition between them. Palmer and Beck (2007) through an indirect task (RDT) have already examined relationship between proximity and luminance similarity cues but not in direct competition. Interestingly, they claimed that luminance similarity (see their Exp. 3) behaves as proximity cues (see their Exp. 1). When two elements repeated consecutively shared the same luminance value (within-group condition) reaction times were slightly faster (although not significant) than in neutral conditions (in which no grouping principle acted). This same pattern was found regarding proximity conditions. Under conditions in which the two elements consecutively repeated did not share the same luminance value or were segregated from the other element (between-group condition), reaction times were much slower than in neutral conditions. However, in our current study both laws compete in the same pattern, it should be noted that Palmer and Beck (2007) already used a subjective scaling phase, prior to the RDT.

In Exp. 2 our results showed that single grouping cues were responded again faster than competing grouping displays. Further, and in agreement with prior findings (Luna et al., 2016; Montoro & Luna, 2011; Montoro et al., 2015, 2017), our analyses indicated that common region grouping cues dominated the perceived organization. For competing stimuli, we found considerably faster RTs when target elements were grouped by common region than when they remained in different ovals. In other words, we observed a bidirectional and asymmetrical interference effect as grouping by connectedness was slowed by the presence of competing common region cues more than vice versa. Of note, this seems to be a consistent finding supported by additional analyses conducted on sub-groups in both objective equating phase and RDT. As in Exp. 1, our hypothesis regarding absence of differences between RDT was unconfirmed. Again, not all participants were capable to match RTs for both principles in objective equating task. Nonetheless, common region advantage effect was also observed in data of those ten participants who managed to match RTs for both single principles in objective equating task.

Schmidt and Schmidt (2013) suggested, that perceptual features that determine grouping strength were not processed in the same way at the phenomenological and the visuomotor levels even though they are both convergent measures of perceptual organization (Kubovy & Gepshtein, 2003; Montoro et al., 2017; Palmer & Beck, 2007). This suggestion received further support from a previous study conducted by Montoro et al. (2017), which reported an unequivocal dominance of common region cues over connectedness even when phenomenological grouping strength single cues was matched, for each participant. Interestingly, the present study goes further by showing that, in competing displays, common region dominance over connectedness prevails even when grouping strength of both single cues was matched at least for part of the sample (i.e. ten participants, RTs in the objective equating task). Similarly, we found that luminance similarity cues exerted greater interference on proximity cues in RDT although fifty-six participants managed to match RTs between both single principles.

Additive models have been developed to explain combined effect of grouping principles (Kubovy & van den Berg, 2008). According to these models, if the final result of the combination of several cues could be predicted from the contributions of its single strengths, then their conjoint effects observed could be considered as additive which could fit a linear model. In this sense, several studies have reported additive effects about competition between different grouping principles (see Peterson & Kimchi, 2013 or Montoro & Luna, 2015, for reviews, but see also Strother & Kubovy, 2012, for other factors that can affect additivity) mostly by means of direct measures of grouping. In contrast, the conjoint effects reported in our study do not apparently fit these additive models as a dominance of common region or luminance similarity cues clearly emerge even when effects for each single principle have been behaviourally matched.

Possibly our data fit a non-additive model of perceptual grouping operations, as previous grouping strength adjustment may not be the only consequence of described findings. It is also crucial to corroborate whether dominance effects of some principles over others is due to previous scaling phase or not. Importantly, RDT used in our study is an indirect measure of grouping operations guided by visuomotor system, which is not have to be necessarily convergent with direct measures of grouping. The suggested dissociation highlights the need of integrate results from experimental procedures that engage different relevant subs-systems of vision when dominance dynamics of perceptual grouping are investigated. Additionally, our results suggest that individual differences might be a critical aspect when measuring grouping, as previous research underline the inspection of interindividual differences (e.g., Claessens & Wagemans, 2005; Luna & Montoro, 2011; Montoro et al., 2017). In this sense, conducted analysis based on sub-groups of participants according to their performance in different tasks illustrate the usefulness of taking into consideration individual variability as a research tool.

To summarize, our data showed that observers responded faster when repeated elements shared same luminance values in competing conditions. In addition, we found again common region dominance effects over element connectedness cues (Luna et al., 2016; Montoro et al., 2017). Remarkably, we introduced for the first time a new objective equating phase to match grouping strength mediated by the visuomotor system. It seems that the use of both a scaling and an objective equating tasks before the RDT might be a more complete procedure to address competition dynamics between different (both intrinsic and extrinsic) principles of perceptual grouping. However, this method will have to be refined and applied to examine interactions between other grouping principles not included in this study and in conjunction with measures that explore brain correlates.

5. Conclusions and future directions

Gestalt laws examined in the current doctoral thesis were originally proposed by Max Wertheimer and his followers in the 20s of the last century. To sum up, these factors describe regularities of our environment to which perception is sensitive to organize our visual scene. For a few decades, these principles were left aside in the study of visual perception and at the beginning of the 21st century Palmer (2003, p. 19) described them as *"among the best known, yet least understood, phenomena of visual perception"*. However, the most incipient criticism is the lack of an exhaustive definition of these rules, as well as the need to develop more quantitative methods and integrated theories on this regard (Jäkel, Singh, Wichmann, & Herzog, 2016). The study of these laws has resurfaced in the last decades and researchers on vision still continue investigating this topic in greater depth in order to obtain more conclusive results.

The main objective of this thesis was to study cognitive and neural mechanisms underlying perceptual grouping operations in visual modality. To achieve this goal, two studies have been carried out (**Experimental Study I and II**). As previously detailed (see Research objectives section) in order to examine interaction dynamics between different grouping cues, terms such as *dominance* have been adapted from the research on dominance processing in hierarchical stimuli (Navon, 1977, 1981). In our experiments, we did not include cooperative conditions between cues, so these effects will not be discussed. Nevertheless, these cooperative interactions deserve to be examined in future experiments devoted to explore these mechanisms underlying perceptual grouping operations for an exhaustive and integrated study of this phenomenon.

In **Experimental Study I**, competition between two classic grouping principles, namely proximity and shape similarity cues, have been explored trough a selective attention paradigm (e.g., Luna et al., 2016). Briefly, our behavioural data showed larger interference effects of shape similarity over proximity cues when both cues compete. In other words, shape similarity cues were dominant when interact with proximity cues in the same display. Similarly, the amplitude of a negative component peaking around 250 ms was modulated by their interaction. The N200 component found, can be considered as the first electrophysiological evidence of the competition between proximity and shape similarity grouping cues. So the modulation of this ERP component renders an indirect brain hallmark of the competition between these two specific cues. Therefore, this N200 effect, could be interpreted as a brain index of the visual salience and/or the processing fluency of shape similarity grouping cues. In other words, the enhanced amplitude elicited by shape similarity conditions could reflect a facilitation of processing when shape similarity single grouping cues guide the organization of the visual pattern as opposed to when shape similarity competing grouping cues are the ones that lead the arrangement of the stimulus set. In shape similarity competing conditions the interference exerted by proximity competing cues is underlying, even though these proximity cues were not addressed. To our knowledge, only Han (2004) has examined the ERP correlates of the competition between these cues. However, our results differ from yours and this could be due to several reasons. One of them, could reside in the displays selected in both experiments, as in our study, we used the same stimuli pattern in both proximity and shape similarity competing conditions. So that, perceptual demands were calibrated in both competing conditions. Similarly, Han (2004) did not control the grouping strength between these grouping principles prior to experimental task. As already mentioned, control the relative grouping strength of each principle before experimental tasks, is a key aspect in the study of these laws (Kubovy & van den Berg, 2008). Otherwise, it is really necessary to underline, that this specific brain index (N200) found in our experiment, only refers to the interaction between these two grouping principles. So, using this method, it would be highly recommendable to carry out more research to find other specific markers of interaction between other pairs of grouping cues. Additionally, in this study, we found larger P300 amplitudes elicited by single displays, as well as by proximity cues, which we have assumed as a correlate of the degree of confidence in decision-making processes during the stage joining perception to action (see Montoro et al., 2015, for a similar account). Our study provides evidence on dominance dynamics about competition between these two perceptual grouping classic laws. In addition, it provides brain markers specifically associated to competition operations, which have been poorly defined or identified throughout previous literature. Nonetheless, in this study, a direct task is used, so it would be highly recommended to search for brain correlates involving other principles of perceptual grouping and also using other tasks of an indirect nature. The inclusion of neuroimage techniques can constitute a fundamental tool in an integrated approach to study these mechanisms underlying perceptual grouping operations (see Sasaki, 2007, for a review). Several ERP studies have examined the temporal course and brain structures related to these visual grouping operations. In fact, some ERP research have pointed out the existence of differences in the time course and brain structures involved in different perceptual grouping factors. The identification of brain markers may help us to gain a better understanding of this phenomenon. Additionally, neuropsychological data, recording ERPs from patients whose injuries are related to these perceptual grouping operations could provide fundamental and complementary evidence on this regard (e.g., Han and Humphreys, 2007).

In **Experimental Study II** we used an indirect task, the repetition discrimination task (RDT). This RDT has previously been used to investigate processes underlying competition between grouping cues (Montoro et al., 2017; Palmer & Beck, 2007). This task, as we previously ventured, does not require explicit and direct attention to grouping cues. The use of RDT provides an unbiased measure of the dominance dynamics on the interactions between different grouping principles, through RTs and response accuracy. Therefore, the use of indirect methods ensures to a certain extent that participants do not develop alternative strategies in their response tendency that are not related to perceptual grouping operations (Palmer & Beck, 2007). In this task, different grouping factors could influence the perceptual organization of visual patterns by facilitating or hindering the performance of observers (that is, reducing or increasing the RTs, as well as their response accuracy). Therefore, RTs differences between conditions have been taken as an indirect measure of the influence exerted by grouping cues. In previous studies, which have used this same paradigm, a pre-calibration phase was implemented to match grouping strength between grouping cues prior to RDT (Montoro et al., 2017; Palmer & Beck, 2007). However, in these studies just a scaling task was used, which involves phenomenological measures, based on subjective judgments of observers on the degree of grouping strength of the cues. However, in our study, two phases have been designed: first, participants performed a *scaling task* based on subjective judgments about match grouping strength between two cues in direct interaction. And then, these same participants, performed an *objective equating task* in which the grouping strength between cues, was matched based on RTs (it was assumed that both cues were equated when differences in average RT was lesser than 10 ms between both single conditions). The inclusion of an objective equating task is our main contribution, as data obtained from both phases enables to compare subjective direct and objective indirect measures in the same experimental design. In this Experimental Study II, two experiments have been carried out, we examined the competition between proximity versus luminance similarity cues (Experiment 1) and the competition between common region versus connectedness cues (Experiment 2). Our results showed larger interference effects of luminance similarity on proximity cues when both cues compete (Experiment 1) and a dominance of common region over connectedness cues in competing displays in RDT (Experiment 2). Specifically, in both experiments all observers performed an objective equating task, complementary to a prior scaling task used in previous research (e.g., Montoro et al., 2017; Palmer & Beck, 2007). However, not all participants managed to match the grouping strength of both principles through this objective equating task in none of both experiments. Moreover, those who did (56 participants, Exp. 1; 10 participants, Exp. 2) then in RDT, their data (RTs) were different between single conditions, and in competing conditions their performance mirrored the data of all sample. As a main finding, it should be highlight that despite the different individual and group results found, under single conditions, the results on the competition between principles is common and shared by all the participants and is continuously found in the multiple analyses carried out, respectively in both experiments. This outcome could be explained tentatively by the non-additive effects of interaction between the different grouping principles, as the product of the competition between them was different from the sum of their individual contribution.

It should be noted that in this study a pioneering proposal has been made about matching grouping strength between different principles in interaction, based on RTs and therefore guided by visuomotor operations. However, individual differences have been observed repeatedly in our data. Recent studies suggest that in experimental psychology research context, there is a tendency to generate unique models about cognitive processes, which may not be representative of the behaviour of the entire population (Botella et al., 2019). So that, in future experiments, it would be desirable to explore different methods of analysis and classification of observers, as well as to test different explanatory models based on additive and non-additive effects of perceptual grouping operations. Similarly, it would be interesting to increase the sample size to verify these effects and examine the relationships between other gestalt laws.

In both Experimental Studies carried out the dominance of one principle has been emerged against another (dominance of shape similarity cues over proximity cues, Experimental Study I; dominance of luminance similarity cues over proximity cues and dominance of common region cues over connectedness cues, Experimental Study II), in spite of a prior control of grouping strength between cues. Perhaps these effects may be due to the intervention of different visual processing subsystems, as Schmidt and Schmidt (2013) previously suggested. It may be also because of individual differences as the Experimental Study II has suggested (e.g., Quinlan & Wilton, 1998; Luna & Montoro, 2011; Montoro et al., 2017; Claessens & Wagemans, 2005). Undoubtedly, one of the main future goals in this field should be to establish more exhaustive study methods that include measures of different nature, and that consider the intervention of different subsystems of visual processing. This could dispel doubts about perceptual grouping operations that are not due to methodology itself. Similarly, qualitative measures should not be underestimated, as they provide valuable information about these visual operations.

Notably, studies about perceptual grouping organization have been focused on visual modality mainly (see Wagemans et al., 2012a, 2012b, for a review). However, these results from research devoted to visual modality could be extrapolated to other sensory modalities in which perceptual grouping operations have also been observed (Spence, 2015). Specifically, these perceptual grouping operations have been examined in haptic sensory modality (see Prieto, 2018, for a more exhaustive review) as the recent development of models based on these gestalt laws in the context of auditory system (Chakrabarty & Elhilali, 2019). Similarly, it is essential to permit that our lab findings would be tested in more applied fields, as both contexts are nourished one from another. Our research could be relevant in fields such as graphic design or learning. Bae and Watson (2014) developed a computer tool that could be implemented in graphic editing programs for selection of elements that share some common characteristics, which would greatly facilitate graphic design processes. In their work, they examined how five of many grouping cues, namely proximity, colour similarity, common region, connectivity, and alignment, can be effectively combined to communicate more successfully structured text and imagery from real world. Among their conclusions, they pointed out that complex structure's communication is more successful if several cues are combined reinforcing each other (cooperation between cues). In addition, they concluded that common region cues are particularly effective while alignment was a weak structural communicator. Koch and Oulasvirta (2016) examined the role of Gestalt laws as heuristic, in the context of interactive layout. Among their results they observed that different grouping factors act in a hierarchical way. Also, our findings could be applied to development of image editing software (Xu et al., 2012). These laws have even been considered in construction of 3D building models (Hu et al., 2018). Hu and collaborators (2018) have been proposed for reconstruct roof parts, generating a complete structural model based on a hierarchical topological tree. Even these laws have been applied from graphic design to a more commercial area, such as commercial billboards. Ettehadmohkam and collaborators (2018) have evaluated the interaction of Gestalt visual laws on perception in Tehran's commercial billboards' texts and graphical images during the year 2015-16. One of the most relevant conclusions that they have reached is that these cues interact with each other, to reinforce their impact. Qin and Li (2017) have also applied these rules of perceptual grouping to design map legends, in the context of cartography, their goal was to communicate more efficiently information contained in them guided by these cues. Gestalt laws have also been interpreted as the rules that guide semantic block detection. Xu and Miller (2016) in the context of web pages and applications (Apps), have developed a model to detect these semantic regularities guided by these grouping laws. All these studies cited above encourage us to continue researching in this context, as it has been proved that the study of these laws of perceptual grouping goes beyond purely basic research and its application could be very useful. In fact, advances made in this research context could have an influence on the development of sensory substitution devices, as some authors already venture, whose source of information may come from different sensory systems (Prieto, 2018; Venini, 2018).

6. References

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Appendix I: Instructions for Experimental Study I

The instructions provided to the participants were the following:

"*In each trial, a fixation point* (a cross) *will appear at the centre of the screen, towards which you should direct your gaze and keep it in that location. Then, a row of seven elements (circles and squares) will be displayed at the centre of the screen. The central element of the row will appear in the same position of the fixation point. The central element can form a group with the three adjacent elements that are on the left or, alternatively, with the three that are on the right. Look at this stimulus example* [the experimenter points out a single proximity stimulus on the screen]. *You can perceive that the central element is grouped with the three elements on the left because it is closer to them than to the three elements on the right. Look at this other stimulus* [the experimenter points out a single shape similarity stimulus]. *In this case, you can perceive that the central element is grouped with the elements on the left because they share the same shape (that is, circles) while the other three elements are different figures (that is, squares). Now, look at these other stimuli* [the experimenter points out several competing stimuli], *which have two competing ways of grouping the central element with the adjacent elements because the central element is near the elements on the right but, at the same time, it shares the same figure (that is, a circle) with the elements on the left. In each block of trials, you will be informed of the grouping cue that you have to attend to in order to respond to either proximity or shape similarity. There will be a practice block before the start of the experimental task, and you will receive feedback for your performance. Your task will be to indicate whether the central element is grouped with the left or right elements according to the designated grouping cue while ignoring the other alternative grouping cue. If the central element is grouped with the three elements on the right you must press the keyboard key "M" with your right index finger. If the* *central element is grouped with the three elements on the left you must press the keyboard key "Z" with your left index finger. Only a single response is accepted in each trial. You have to respond as quickly as possible without making errors. Once you respond, the next trial will immediately begin with a fixation point displayed on the screen. When you finish a block of trials, you will be notified and you will be able to take a short break if you want*."

Appendix II: Instructions for Experimental Study II

The instructions provided to the participants were the following:

Experiment 1: Proximity vs. Luminance Similarity.

Scaling Task:

"In this first phase, your task will be to manipulate the distance between the geometric elements [the experimenter points out a row of eight elements, which will always be grouped in pairs for its luminance in turn by the distance]. You will have to increase or to decrease the distance of these elements until their grouping strength or degree seemed as equally strong as the grouping strength or degree of the luminance similarity cue [the brightness of the elements], so that the visual grouping of the elements in pairs were equally salient in figures closer to each other and in in figures that are coloured with the same luminance value. Your judgments should be based on the grouping strength or degree or subjective salience of the cues. You will perform one practice trial and eight scaling trials: four trials starting with the closest distance between elements (i.e. ascending trials) and the other four beginning with the farthest distance between elements (i.e. descending trials). You can manipulate the distances by pressing the right (to increase the distance) or left arrow (to decrease the distance) keys of the keyboard with the index fingers of both hands. There was no time limit. When you complete the eight trials, the program will record your answers and you will have to wait for instructions for the next phase of the experiment."

Objective Equating Task:

"In this second phase, your task will consist of indicate the shape of the consecutive repeated pair of elements in adjacent positions which may be two circles or two squares [the experimenter points out a row of nine elements]. In some trials these elements will be exclusively closest to each other in pairs while in other trials they will share in pairs the same luminance. You have to respond by pressing the "Z" key if you identify two consecutive squares, using the left index finger or the "M" key if you identify two consecutive circles, using the right index finger. Only a single response is accepted in each trial. At the beginning, you will perform a block of practice in which you will receive feedback and then you can perform up to ten experimental blocks in which you

will no longer receive feedback. In each trial, a fixation point (a cross) will appear at the centre of the screen, towards which you should direct your gaze and keep it in that location. Then, a row of nine elements (circles and squares) will be displayed at the centre of the screen. You have to respond as quickly as possible without making too errors. Once you respond, the next trial will immediately begin with a fixation point displayed on the screen. When you finish a block of trials, you will be notified and you will be able to take a short break if you wish."

Repetition Discrimination Task:

"In this third and final phase, the instructions are the same as the previous phase. Your task will consist of indicate the shape of the consecutive repeated pair of elements in adjacent positions which may be two circles or two squares [the experimenter points out a row of nine elements]. In some trials these elements will be exclusively closest to each other in pairs [proximity cues] while in other trials they will share in pairs the same luminance [luminance similarity cues]. The novelty is that in other trials could be present at the same time elements closest to each other or elements that share the same luminance value [proximity and luminance similarity cues interacting at the same time]. You have to respond by pressing the "Z" key if you identify two consecutive squares, using the left index finger or the "M" key if you identify two consecutive circles, using the right index finger. Only a single response is accepted in each trial. At the beginning, you will perform a block of practice in which you will receive feedback and then you perform up to four experimental blocks in which you will no longer receive feedback. In each trial, a fixation point (a cross) will appear at the centre of the screen, towards which you should direct your gaze and keep it in that location. Then, a row of nine elements (circles and squares) will be displayed at the centre of the screen. You have to respond as quickly as possible without making too errors. Once you respond, the next trial will immediately begin with a fixation point displayed on the screen. When you finish a block of trials, you will be notified and you will be able to take a short break if you wish."

Experiment 2

Scaling Task:

"In this first phase, your task will be to manipulate the thickness of the connectors which joined the geometric elements [the experimenter points out a row of eight elements, which will always be grouped in pairs surrounded by ovals and in turn by connectors]. You will have to increase or to decrease the thickness of these connectors until their grouping strength or degree seemed as equally strong as the grouping strength or degree of the common region cue [the ovals that surround the elements], so that the visual grouping of the elements in pairs were equally salient in figures joined together by connectors and in figures included in ovals. Your judgments should be based on the grouping strength or degree or subjective salience of the external elements (that is, ovals or connectors), which does not imply that the inductors had to be equated in physical thickness (that is, it does not mean equalizing the number of pixels of the connectors based on the number of pixels of the ovals). You will perform one practice trial and six scaling trials: three trials starting with the lowest thickness value (i.e. ascending trials) and the other three trials beginning with the highest thickness value (i.e. descending trials). You can manipulate the values of the connectors by pressing the right (to increase the thickness) or left arrow (to decrease the thickness) keys of the keyboard with the index fingers of both hands. There was no time limit. When you are sure of your decision, you verbally confirmed your final choice, and left the screen static so that the experimenters could record the specific value of thickness that you have selected."

Objective Equating Task:

"In this second phase, your task will consist of indicate the shape of the consecutive repeated pair of elements in adjacent positions, which may be two circles or two squares [the experimenter points out a row of nine elements]. In some trials these elements will be exclusively connected by bars while in other trials they will be only surrounded by oval but you have to ignore these external elements and only pay attention to the shape of the figures in order to make the task. You have to respond by pressing the "Z" key if you identify two consecutive squares, using the left index finger, or the "M" key if you identify two consecutive circles, using the right index finger. Only a single response is accepted in each trial. At the beginning, you will perform a block of practice in which

you will receive feedback and then you can perform up to ten experimental blocks in which you will no longer receive feedback. In each trial, a fixation point (a cross) will appear at the centre of the screen, towards which you should direct your gaze and keep it in that location. Then, a row of nine elements (circles and squares) will be displayed at the centre of the screen. You have to respond as quickly as possible without making too errors. Once you respond, the next trial will immediately begin with a fixation point displayed on the screen. When you finish a block of trials, you will be notified and you will be able to take a short break if you wish."

<u>Repetition Discrimination Task:</u>

"In this third and final phase, the instructions are the same as the previous phase. Your task will consist of indicate the shape of the consecutive repeated pair of elements in adjacent positions which may be two circles or two squares [the experimenter points out a row of nine elements]. In some trials these elements will be exclusively connected by bars [connectedness cues] while in other trials they will be only surrounded by ovals [common region cues]. The novelty is that in other trials could be present at the same time the ovals that surround the elements such as connectors [common region and connectedness cues interacting at the same time]. You have to respond by pressing the "Z" key if you identify two consecutive squares, using the left index finger or the "M" key if you identify two consecutive circles, using the right index finger. Only a single response is accepted in each trial. At the beginning, you will perform a block of practice in which you will receive feedback and then you perform up to six experimental blocks in which you will no longer receive feedback. In each trial, a fixation point (a cross) will appear at the centre of the screen, towards which you should direct your gaze and keep it in that location. Then, a row of nine elements (circles and squares) will be displayed at the centre of the screen. You have to respond as quickly as possible without making too errors. Once you respond, the next trial will immediately begin with a fixation point displayed on the screen. When you finish a block of trials, you will be notified and you will be able to take a short break if you wish."

Appendix III: Informed Consent

Experimento: ____________ *Código Participante:* ________

DECLARACIÓN DE CONSENTIMIENTO INFORMADO

D./Dª ____

He sido suficientemente informado sobre la utilidad, objetivos y metodología empleada en el proyecto de investigación para el que se ha solicitado mi colaboración, y se ha respondido a todas mis preguntas al respecto.

Comprendo que mi participación es voluntaria y que puedo retirarme del estudio cuando desee, sin necesidad de exponer el motivo y sin que ello implique ninguna repercusión negativa para mí.

Por todo lo cual, **PRESTO MI CONSENTIMIENTO** para participar en el proyecto de investigación anteriormente citado.

En Madrid, a _____ de ___________ de 2_____

Fdo: ______________________________