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STUDYING THE "NEURAL BEHAVIOR": A PERSPECTIVE ON BRIDGING THE GAP BETWEEN BEHAVIORISM AND NEUROSCIENCE AND ITS APPLICATIONS TO LANGUAGE TEACHING STRATEGIES

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GENERAL INTRODUCTION

The purpose of the present thesis is to point out the development of a particular line of research aimed at bridging the gap between the Neurosciences and Behavior Analysis, the science of behavior and learning, by studying verbal and non-verbal behavior in human brain through the use of functional imaging (fMRI) techniques. This research line has been developed to allow the merging and interaction between the two sciences, in order to study events in the human brain which meet their overt counterparts (public responses). Also, it is aimed at exploring the potential practical clinical implications of extending the study of human behavior to brain processes, in terms of both producing new cognitive-behavioral neuromarkers of neurological and psychiatric diseases and, more importantly, suggesting new strategies for teaching language to individuals with learning disabilities, thus contributing to develop not only a more complete analysis of “verbal behavior”, but also an enhanced technology for teaching it.

Burrhus Frederic Skinner (1938, 1953, 1957, 1974) has written about the possibility of exploring the “part of the universe” residing within our organism, which he calls “the world within the skin” (1974) and to which he has devoted a considerable deal of his work. He argues that the same account can be given to the “private” (covert) behavior as to the “public” (overt) behavior (Skinner, 1953, 1957, 1974). One of the very first considerations he makes in this regard is that the intrinsic nature of the events occurring in the “inner world” should not be a reason to consider them differently with respect to the environmental events taking place in the publicly observable world; in this order of ideas, the skin must not be considered a boundary to study behavior, but yet, a “complete account” for private behavior is to come from some integrative support of another field, that Skinner identified as the field of physiology (Skinner, 1974), and that we can today identify as modern neurosciences.

The world of private events encompasses motivation, emotions and feelings, but it also deals with some form of behavior, like thinking, which is characterized by a “different magnitude” with respect to other responses. The behavior-analytic literature has explored a possible conceptual formulation of the role of private events, and that would be the object of part of the following discussions in this work. What the study of anatomy and physiology of the brain through some now available real-time and non-invasive advanced techniques, like fMRI, can bring is making private events observable and turn them into a corresponding dimension of public events. This unique kind of support brought by neuroscience to the science of behavior needs not to correspond to uncovering some kind of correlate of behavior, but needs instead to make a detailed and thorough analysis of the brain processes underlying overt behavior finally possible and extend the application of Skinner's conceptual analysis of behavior also to neural events.

The first experimental application of this extended conceptual perspective resulted in what our research group has called an "analysis of neural behavior" (Pappalardo et al., 2019), and consists, in the present work, in an investigation of the possible correspondence between neural events (namely localized occurrences of cooperative neural activity) and their public counterpart. This correspondence has taken the form of possible measures of behaviors in the brain.

In the book *Verbal Behavior* (1957), the most detailed formulation of the behavioral conceptualization of language and communication, B.F. Skinner establishes the conceptual frame of reference for an environmental account of language, and strongly sets his analysis apart from the formal linguistic model provided by Noam Chomsky. Also, when providing an analysis of solving complex tasks like "mental arithmetic" problems, Skinner advances the conceptualization of a behavioral chain of events beginning with a public verbal stimulus and ending with a public response and whose intermediate links "turn" into private verbal behavior (but can recover their public form) because they "loose the strength needed to be perceived publicly" (1957). These public responses dropping below the "strength" level for overt emission belong to the realm of private behavior, which, for Skinner, is just public behavior on a "smaller scale" of detection (Skinner, 1974). A wide further aim of the present work has then been investigating the localization of the publicly observed behaviors in the brain, namely highlighting the brain areas where cerebral behaviors underlying public behaviors occur. This investigation has led to a detailed analysis of "verbal behavior" in the brain, which allows the study of language utterances from a behavioral perspective and thus encompassing a functional evaluation of the controlling variables of linguistic production. This has been done by highlighting and differentiating the neural activity patterns that are specific to each one of the classes of verbal behavior to whom B. F. Skinner gave the name of *verbal operants*, and to analyze the spatial distribution of neural resources during the production of verbal responses pertaining to some of these classes[1], which also enables to point out the possible neural frame of reference for both the functional independence of the verbal operants (different environmental stimuli controlling the verbal responses in a differentiated fashion) and the multiple control of verbal behavior (some verbal responses being controlled by a particular *set* of stimuli). In fact, further analyses have been carried out on both the convergence and the functional independence of the different neural patterns observed (which allow to specifically identify a verbal operant in terms of amount and distribution of neural resources), once again investigating the neural basis of the Skinnerian conceptualization of language. The analysis of the convergence between the patterns has in particular assumed the form of the study of the neural loci of overlapping of the patterns themselves. If the overlapping of neural patterns associated to each verbal operant is detected, it explains not only the presence of multiple control of verbal behavior, but also how frequent it is in the "stream" of verbal behavior we ordinarily engage in, and reveals the neural underpinnings of the stimulus control transfer procedures clinically implemented to teach new verbal repertoires. The descriptive level of analysis provided by the experiments[2] that we have run led us to define neural "fingerprints" typical of the verbal operants studied, providing objective parameters of the neural activity that characterize every single verbal operant. Decomposing and analyzing the spatio-temporal pattern of brain activation led to also explain private multiple mediation and paved the way to the conceptualization of public verbal responses as final links of complex behavioral chains beginning with an external (public) stimulus and ending with an overt (public) response, but whose intermediate links are a series of covert (private), neural behaviors.

As said previously, defining a common conceptual framework between Neuroscience and Behaviorism and systematically studying the single units of analysis of verbal behavior within the brain environment can lead to deriving considerations of applied nature, aimed at developing new teaching procedures for verbal behavior. Particular interest was devoted to the topic of the acquisition of complex verbal repertoires, specifically focusing on the analysis of the brain processes corresponding to a particular verbal operant, the *intraverbal*. Intraverbal behavior was studied in the form of word association, and possible teaching strategies were investigated based on the results of the study of this and of the other verbal

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[1] Spatial distribution of neural resources has been studied for the Tact, the Echoic, the Textual and the Intraverbal operants, and a detailed analysis will be found in Chapter 4.

[2] See Chapter 4.

operants in the brain environment. The possibility of implementing a *specific* training of the neural nodes (brain areas of intersection) which are common to different neural patterns -the ones subserving the public repertoires of interest- was also investigated. This specific training can be conceptualized as a transient neural antecedent condition in which the probability of emitting a target response increases so that such response can be possibly strengthened through proper consequent contingencies (reinforcement consequences).

Bridging the gap between the Science of Behavior and the Neurosciences means to experimentally show that private behavior follows the same laws as public behavior. Imagine every single public response like the top of an iceberg which is made up by a series of other private responses which are emitted on a neurological level and that could be investigated choosing different levels of complexity. If private behaviors are to be considered as the "bricks" of complex and hybrid private and public behavioral chains, a better understanding of the role they play during learning and a conceptualization of the relationship between "operant conditioning" and brain functioning can become very useful, especially if its results are used in the treatment of learning disabilities and particularly of autism.

The data included in the present thesis are the product of the research activity I have conducted in a research group composed also by other PhD students, and parts of a manuscript this research group has worked on and that is being prepared for publication will be herein included.

SECTION I: CONCEPTUAL FRAME OF REFERENCE

CHAPTER 1

A CONCEPTUAL AND PHILOSOPHICAL FOUNDATION FOR THE CONVERGENCE BETWEEN BEHAVIORISM AND NEUROSCIENCE

1.1 Introduction

The perspective of an interface between Behaviorism and Neuroscience, and of bridging the gap between them, is conceptually founded on the possibility of showing that the laws of behavior are valid in the brain environment too, thus creating a unified theory of behavior to encompass the laws operating in the nervous system and the ones applying to neural responses.

In 1938, when no advanced methodological tools to explore brain activity were available, B. F. Skinner already addressed what turned out to be one of the major aspects of a comprehensive science of behavior (Palmer, 2011): the relationship between public behavior and the neural events that account for it. He pointed out that before a neurological fact may be established to account for a public response, some degree of quantitative correspondence between this neurological fact and the observable behavior has to be shown. He thus made clear that eventual technical advancement would not be all is to be needed to generate the desired convergence between the laws of public behavior and the nervous system, but that, at the same time, the concept of a separation of methods and subject matters between these two same systems of laws has to be abandoned. He highlighted that much may be obtained from a convergence of the two sciences, which would be then be able to produce comparable data.

Skinner suggests that it's not only a matter of observation (having technical instruments to observe what is going on in the brain at the private level), but also of being able to "produce these conditions at will", that's to say to manage to bring some specific responses under the control of a particular set of private stimuli, thus modifying the brain functioning[3].This process is not supposed to modify the 3-term contingency, but, instead, to include private events in it. Discriminative stimuli that exert a modifying effect on behavior would then be

[3] The reader could find perhaps interesting to explore throughout the present work the implementation of specific training modalities aimed at momentarily modifying the degree of excitability of neurons in a particular brain region, and opening the possibility of investigating changes in anatomical, functional and effective connectivity.

of both public and private nature, the responses they evoke could also be private or public themselves, and both can contact private and public consequent stimulus changes. The following quote summarizes the arguments exposed, and is one in which Skinner clearly acknowledges the possibility of a convergence between behavior analysis and neuroscience:

"The physiologist of the future will tell us all that can be known about what is happening inside the behaving organism. His account will be an important advance over a behavioral analysis, because the latter is necessarily "historical" – that is to say, it's confined to functional relations showing temporal gaps. Something is done today which affects the behavior of an organism tomorrow. No matter how clearly that fact can be established, a step is missing and we must wait for the physiologist to supply it" (Skinner, 1974, p. 236-237).

In the meantime, however:

[…] We must be content with reasonable evidence for the belief that responses to public and private stimuli are equally lawful and alike in kind. (Skinner, 1945, p.272)

suggesting that even in the absence of additional support for observing and managing to understand what happens at a different, perhaps a more complex, private level, it is not to doubt that there is no difference in that both (private and public) contingencies depend on the same laws. Still in 1945 and still in the context of his "toothache" example, Skinner wrote:

"The response "My tooth aches" is partly under the control of a state of affairs to which the speaker alone is able to react, since no one else can establish the required connection with the tooth in question" (p. 272).

In the first place, this appears to anticipate the idea of the "missing step" (Skinner, 1974) between what happens at a private level and what can be observed in the public domain[4] and that Skinner acknowledges a gap to account for, and then he continues:

"Whenever it becomes possible to say what conditions within the organism control the response "I am depressed", - or "my tooth aches" for example, and to produce these

[4] See the quote from *About Behaviorism* above.

conditions at will, a degree of control and prediction characteristic of responses to external stimuli will be made possible" (p. 272).

This gap is then clearly represented by private conditions that can control a public response, but that are to be accounted for – known and made reproducible- in order to establish a thorough degree of prediction and control over the public response itself and not to just "infer the private event", because in a "complete" science of behavior we need to be able to actually account for the private event.

In the last decades, the Science of Behavior and Neuroscience have traced their tracks in a parallel way, producing their own analyses, literature and conceptual discussions. But let's deal with these two sciences separately for a moment, before exploring the perspective of their convergence.

1.2 Behavior Analysis: An overview

The publication of Skinner's *the Behavior of Organisms* (1938) formally marked the moment in which the experimental branch of behavior analysis was born. In fact, the science of behavior comprises three domains: one pertaining to its philosophy, one to basic research (the Experimental Analysis of Behavior – EAB) and one concerning its application to improve socially significant behavior (Applied Behavior Analysis – ABA). *The Behavior of Organisms* was the product of Skinner's laboratory work of seven years (form 1930 to 1937) and was aimed at providing a scientific account of all behavior. Once again, Skinner found that an important step was missing from the paradigm of stimulus-response relations provided by psychology at the time[5], and specifically he believed that S-R- psychology could not explain all behavior. He found that there were behavioral responses with more "voluntary" features with respect to the reflexes described by Watsonian behaviorism and for which Watsonian behaviorism could not provide an account for. But, instead of relying on unobservable and not experimentally manipulable variables presumably existing inside the organism (hypothetical constructs), like cognitive processes, Skinner found that the environment itself was the place to look for the determinants of behavior. The importance of the antecedent variables notwithstanding, he gathered impressive evidence that behavior is changed by the stimuli (consequences) that immediately follow it and with which it has

[5] i.e. *Watsonian behaviorism.* Watson argued that an objective study of behavior should rely on the direct observation of the relationship between environmental stimuli (S) and the behavioral responses (R) they are able to evoke. That is why Watsonian behaviorism is known as S-R psychology.

a relation of dependence (contingency). That's how Skinner provided a new frame of reference to study behavior, differentiating between respondent (reflexive) and operant (selected by consequences) behavior. And that's how an experimental approach to the study of behavior was born, an approach that made demonstration of the presence of functional relations between behavior and environmental events possible (Cooper, Heron, & Heward, 2020), and that led to the discovery of the basic principles of operant behavior[6].

1.3 Neurosciences and the Study of Brain Functioning

Neuroscience, as a broad discipline integrating the contributions of different sciences associated with neurophysiology and studying the brain, is aimed at understanding the biological foundation for what is commonly referred to as "mental activity". It managed to bridge the gap that neuroanatomists and neurophysiologists were looking for through the development, among other, of imaging techniques in the course of the second half of the last century. From 1960s, in fact, it is possible to think of neuroscience as a set of sciences and techniques that allow to observe and study brain processes. fMRI in particular is a very powerful investigating tool that can be applied to the study of complex brain networks to derive an analysis of brain functional systems. As it provided the solution to different methodological and interpretative problems related to the analysis of brain activity, fMRI application has increased, and its widespread application, even if it's not yet able to provide an extensive explanation of functional phenomena and address all the possible difficulties related to them, has led to the production of a large amount of relevant neuroscientific research and to learn a great deal of information about brain functioning and about its functional organization, in a completely non-invasive way[7]. Across the years, the study of the brain at this level was supported by the development of different types of acquisition sequences and of specific methodologies allowing not only the acquisition of functional data, but also their subsequent processing.

[6] These discoveries and the methodological features of the experimental approach developed by B.F. Skinner continue to be the empirical foundation of behavior analysis today (Cooper, Heron, & Heward, 2020).

[7] In addition to the very good compromise between spatial and temporal resolution offered by fMRI techniques, the unique advantage of fMRI with respect to other imaging techniques is the possibility of simultaneously evaluate "coregistered" structural (anatomical) and functional data.

Apparently, Behavior Analysis and Neuroscience have traced their own tracks in an independent way with respect to each other. The very question to be answered then is if a developed convergence between them can generate "an *analysis of neural behavior*" to be integrated in a science of behavior and used "for conceptual and applied purposes" (Pappalardo et al., 2019), thus finally fulfilling B.F. Skinner's expectations about Neuroscience.

1.4 The Role of Private Events in the Science of Behavior

Skinner's work was revolutionary in several ways, and extremely influential in guiding the application of the science of behavior. So was his perspective on the philosophy of this science, Behaviorism, to which he dedicated an entire work in 1974. Behaviorism, he wrote, asks questions like: "Is such a science really possible? Can it account for every aspect of human behavior? What methods can it use? Are its laws as valid as those of physics and biology? Will it lead to a technology, and if so, what role will it play in human affairs?" (p. 3). Clearly, Skinner's behaviorism had some revolutionary features too, because it did not reject the existence of "mental events" but viewed them as behavior responding to the same laws governing publicly observable behavior and to be studied with the same tools.

He argued that there is a part of the environment "which is contained within the skin of each of us. There is no reason why it should have any special physical status because it lies within these boundary, and eventually we should have a complete account of it from anatomy and physiology. […] it would seem foolish to neglect this source of information just because no more than one person can make contact with the one inner world. Nevertheless, our behavior in making that contact needs to be examined" (Skinner, 1974, p. 24).

According to Skinner, it was then necessary to correct the mistake made by methodological behaviorists in ignoring the examination of the private world[8] and to go to the "heart" of radical behaviorism by providing a different account of inner events.

[8] In About Behaviorism (1974) he says: "Covert behavior is also easily observed and by no means unimportant, and it was a mistake for methodological behaviorism and certain version of logical positivism and structuralism to neglect it simply because it was not "objective". It would also be a mistake not to recognize its limitations. It is far from an adequate substitute for traditional views of thinking.it does not explain overt behavior: it is simply more behavior to be explained" (p. 115). This passage was also quoted by Carbone (1981), in an article which provides a description of private events from a radical behavioral perspective, noting that Skinner "acknowledged the existence of an inner world" (p. 110). It is, however, an

Not only in *About Behaviorism*, but also in other of his works B.F. Skinner acknowledged the great deal of importance that a unified perspective between the science of behavior and neuroscience can have. As previously discussed, and also pointed out by Timberlake, Schaal, and Steinmetz (2005), Skinner's expression of interest in the relation between "the laws of behavior and the laws of the nervous system" is to be found back in 1938, when he dedicated an entire chapter entitled "Behavior and the Nervous System" in *the Behavior of Organisms* to the convergence of the two perspectives. Later, in *Science and Human Behavior* (1953), while delineating "a science of behavior" and discussing how much of a complex subject matter behavior can be, he argued that the difficulty of extracting lawful relations for behavior comes from its complex intrinsic nature, which is also engendered by some degree of inaccessibility. Still in *Science and Human Behavior*, in a chapter dedicated to "Private events in a natural science", Skinner discusses this complexity and this level of inaccessibility of behavior; his work is in fact disseminated with examples reflecting the issue of the limited accessibility of private events (see, for instance, the "toothache" example, 1945; 1953). He argues that since the issue is not easily addressable, it can be responsible for the behavior analytic community to avoid the problem, which, in contrast, is an important one and needs to be addressed. Moreover, he points out that this particular issue yields a dualistic perspective over behavior, in which public phenomena are separated from the ones that take place within the skin of a single individual, and that this opens to deferring to hypothetical constructs (i.e., "the mind") and mentalistic explanations. According to Skinner, this scenario should instead push a science of behavior to finally provide an environmental explanation for what happens within the skin: instead of assuming the existence of two different "worlds", a unitary account is to be provided, one that *makes the private public*.

The question then becomes how a functional analysis is still possible in the presence of such inaccessible variables.

Already in 1945, Skinner acknowledged the importance of a more complete conception of human behavior, a conception in which an operational analysis of the account of private stimuli on the emission of behavior is to be performed to reach an "independent knowledge

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important quote in highlighting how the issue of the accessibility of private events was approached carefully by Skinner and not without concern: a radical behavioral account of private events relying on physiology and technical advancement will open a certainly more complex view over behavior, and will without doubt set the need to explain more complex and certainly a greater amount of phenomena.

of the stimulus" (p. 272). Still in 1945, Skinner acknowledges the need to find some kind of solution in "improved physiological techniques" (p. 272) and therefore to bridging the gap between physiology and behaviorism. Techniques deriving from another science would then make possible to perform a more thorough functional analysis of the independent variables causing the emission of overt behavior, and even to enhance the prediction and control over it by being able to replicate at will the private conditions that evoke overt responses.

All these considerations notwithstanding, Skinner argued that the process of making private events public is not to be solved only by the use of more advanced technical equipment. The point of observability is still a valid one, because:

"The line between public and private is not fixed. The boundary shifts with every discovery of a technique for making private events public. Behavior which is of such small magnitude that is not ordinarily observed may be amplified". (p. 282),

but he was still concerned that the "instrumental amplification" would not be all, because "how the organism reacts to these events will remain an important question" (p. 282).

In Skinner's (1974) opinion, the role of "the physiologist of the future" had a great deal of importance because he could unveil the historical gaps existing between inner operant learning and its publicly observable products, the "missing step" (Skinner, 1974) in the continuous changes that affect the living organisms, thus completing the laws of a science of behavior with additional valuable information about inner events. The "black box" became the metaphor used to refer to something to be explored with an environmental approach.

In *Science and Human Behavior* Skinner extended his discussion on private events to conditioned and operant seeing at the private level, i.e., the generation of private visual stimuli possibly evoked by an external stimulus or a private one and reinforced by private as well as public stimuli. It will be discussed later in this work how an important point this is, with regard to the study of the specific distribution of neural resources when producing verbal behavior and of how a convergence of particular patterns of distribution of neural activity would constitute the basis of the conceptualization and implementation of specific teaching strategies for the private neural activity and public response outputs of verbal repertoires, even complex ones. It is incredible how actual Skinner's discussion remains, and how it fits more modern discussions on the possible equivalence in the brain processes related to perception and imagination. In the same section of his book, Skinner delineates an analysis of a possible behavioral chain[9] containing private and public links, in which the image produced by a private seeing response may also function as a discriminative stimulus that evokes further responses, either at the private or the public level. Also, when he talks about "Search and Recall" (1974, Chapter 7), and provided that there is no such thing as the storage of information in the brain[10], he conceptualizes recall as behaving in the same way as if the stimulus was present. That is because the behavior of an organism is affected by the contingencies, it does not store them but is able to create them again through specific synaptic pathways established by the exposure to the stimuli.

Skinner so clearly explains once again that there is no difference in nature between private and public behavior, but that they only pertain to two different scales of observation (1974). He refers to private behavior as behavior which occurs on a smaller scale than the one on which public behavior occurs, "on a scale so small that that it cannot be detected by others" (Skinner, 1957, p.114), thus on a covert level, like "public behavior in miniature".

While they have been pretty largely discussed and conceptualized by B.F. Skinner, the role of private events has probably not been object of study in behavior analysis in such a focused way as he would have expected, or at least not as deeply as it has been in other disciplines, such as psychology and neuroscience, even if from different conceptual and methodological standpoints. Yet, Anderson et al. (2000) claim that:

> "the field's silence about private events unnecessarily limits the theoretical or conceptual understanding on which applied behavior analysts base their work. Further, a large gap exists in behavior analysis that is obvious to other behavioral scientists, to our students, and to our potential students, giving them the unfortunate impression that behavior analysis is unwilling, or worse, unable to deal with certain important and interesting behavioral phenomena" (p. 4).

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[9] Skinner's conceptualization of private events as parts of complex behavioral chains are clear in several passages of his works. For example in Science and Human Behavior, he notes: "But the private event is at best no more than a link in a causal chain, and it is usually not even that. We may think before we act in the sense that we may behave covertly before we behave overtly, but our action is not an "expression" of the covert response or the consequence of it. The two are attributable to the same variables" (p. 279).

[10] "there are no copies of things inside the body" (About behaviorism, p. 96).

Interestingly, the authors make considerations on the importance of including, at the theoretical as well as the empirical level, thinking, feeling, and other private events in both the conceptualization and the applied work for behavior analysts. This means not only dedicating them the great deal of attention like other disciplines have done before, but also with the same analytical approach our science has instead dedicated to the study of public behavior. Their work is the first of a series of papers from a symposium on the role of private events in a science of human behavior[11] and on the possible conceptualizations of private events within a behavior-analytic framework, with the final aim to further enrich the discussion about this topic and prompting thinking and research in its regard.

They describe the most important points of debate concerning private events as first of all dealing with the possibility of actually including them within a natural science of human behavior and acknowledging them a place in it on the conceptual and philosophical level, and subsequently getting to ascertain if these particular events can significantly affect our public behavior. These questions answered, the next question would become if studying private events can lead to some kind of applied implications, which practically means asking ourselves as a scientific community if there is a possibility that an analysis of private events can itself lead to the development of new teaching strategies for different classes of overt responses. It is then clear how this reopens, in the behavior analytic literature, a discussion that had already been started by B. F. Skinner in his work (1938, 1945, 1953, 1957, 1974), but the debate seems to remain still quite open, unless the answers begin to come from some kind of new platform of shared and integrated knowledge, the same that B. F. Skinner was advocating for, and that seems more and more to feel right in the form of a merging between the science of behavior and the neurosciences[12]. One of the most valuable things, anyway, is that an open discussion can prompt continuous investigation about what role private events can have in our science and how we can not only best conceptualize them, but also use this conceptualization to guide effective treatment. Namely, it can socially impact significantly the lives of individuals by designing new teaching strategies based on this enhanced conceptualization.

[11] It is a series of four papers that were published in a Special Section on Private Events of The behavior Analyst (Vol. 23(1); Spring 2000).
12 As Zilio (2016) notes, "Skinner used different terms such as physiology, neurology, and neural science when referring to the sciences dedicated to studying the physiological mechanisms related to behavior" (p. 198). As for the Zilio paper and in the contemporary literature on the topic, also in this work the term neuroscience will be the one used.

The discussion can be better outlined by reviewing the perspective of the different schools of behaviorism that have dealt with the role or status of private events. An important point would be also providing a definition of what is a private event. It is to recognize that this point could be the object of a discussion itself[13], but let's refer to private events as to thoughts, feelings, emotions, physiological responses or part of emotional responses, internal states of motivation, but also responses that happen at the neurological level. We would then be referring to the entire complex of events that are only observable to the individual who is experiencing them, that's to say to events that occur within the boundaries of the skin of the person, to use Skinner's words (1974). Another interesting point could be the degree of separation that has to be made between this kind of events which happen within a person and the public behavior that this same person engages in. This would lead us to conceptualize different kinds of roles private events can have, also in the perspective of considering them as part of complex chains of behaviors with some "hidden" links in the internal part of the body and some external parts that coincide with the publicly observable behavior (overt output of the behavioral chain). The hybrid (private and public) nature of these behavioral chains could be accompanied by different levels of complexity, which parallel the extreme complexity of the brain environment (with millions of neurons involved) and of the neural processes that subserve the expression of public behavior. Like Anderson et al. (2000) claim, a behavioral conceptualization of private events does not need to encompass any elements of mentalistic explanations, nor to consider private behavior and public behavior as two different classes of events; it needs, however, to be based on the most parsimonious[14] and the best environmental explanations that can be given about them.

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[13] In this same article (Anderson et al, 2000) a point is made about the undifferentiated nature that tends to be associated to private stimuli and private responses by the behavior-analytic community in the discussion on private events. In an article containing extracts from a discussion on private events, Palmer et al. (2003) report a suggestion for a "sharper distinction between the terms *stimuli* and *responses*" (and response product) made by Jack Michael with the aim of bringing exceptional clarity to the matter, especially when dealing with the covert part of the environment.

[14] The potential issue of parsimony vs interpretation is addressed in the behavior-analytic literature dealing with the topic of private events (Palmer et al, 2004). In its regard, Palmer argues that it is possible to interpret incomplete data (i.e. data related to phenomena which are not directly reachable and measurable), as long as the interpretation relies on basic principles that have been experimentally established and as long as it helps to "resist the temptation to invent magical solutions" (p.115). A possible takeaway point could be that just because it is more difficult to study it, that doesn't mean covert behavior is less real, and that the most parsimonious account for its role can be based on an interpretation, if any other solutions are viable and if the ultimate risk is to completely ignore them.

But let's return to the different schools of behaviorism and to how their different positions have impacted the status quo of the discussion about private events in the behavior analytic community. The status, the importance, and actually the need to give private events a role in a science of human behavior has changed as different schools of behaviorism have developed. The topic of private behavior has been addressed differently by Methodological Behaviorism, Cognitive Behaviorism and Radical Behaviorism. For the school of Cognitive Behaviorism, it is possible to study unobservable events, which are cognitive events, because they can play a role in the mediation of overt behavior and in learning. But cognitive events are in fact hypothetical structures, as memory or information processing networks, that's to say their conceptualization is not based on real environmental explanations. Methodological behaviorism, in contrast, is centered around the study of behavior that can be observable by other people (Skinner, 1953, 1974). It was originated with the intention of improving the field of psychology by bringing its attention to phenomena that are not related to introspection, but that are much closer to the observable and objective realm. The core of the discussion here, then, is that the focus of analysis and investigation should not be related anymore to mental processes which are not observable and not measurable, but towards some other kinds of phenomena for which an environmental explanation, not an inferential one, can be provided. For methodological behaviorists, private events, given their definition- events that are observable only to the person who is experiencing them- cannot be the object of discussion or study, because they are not observable by other people. According to their philosophy, consequently, the study of "the world of the mind" is to be abandoned because no agreement can be obtained on events that are "unobservable". That -completely shutting down any interest on the inner world- is how they dispose of the issues raised by mentalism taking the place of environmental explanations. Of course, ignoring private events cannot be the solution. That's why another school of behaviorism has developed, radical behaviorism, which differs from the other two schools of behaviorism because it does not deny the possibility of observation- even if self-observation- of certain events and thus embeds private events in its inquiry of natural phenomena, questioning about the nature of private events and about how and how much of them can be observed. As Anderson et al. (2000) point out, radical behaviorism is based on a "monistic" view of behavior in which public responses, which are external, overt physically observable responses, and private responses, the ones that occur within the body, do not differ.

To say it with Skinner's (1974) words, Radical Behaviorism brings back balance to a perspective on behavior that has completely ruled out a great deal of important events – inner events- controlling human behavior (private stimuli) and being themselves human behavior (private behaviors, like thinking). It has somehow repaired the damage brought by a certainly more simplistic view of behavior, but that risked anyway to conduct again the analysis towards mental fictions. Radical Behaviorism also brings another important point to the discussion, which is related to the observable status that private events can possibly acquire and that will allow a functional study of the neural events, thus opening the way to a more comprehensive science of behavior.

Anderson et al. (2000) propose a possible conceptualization of private events as discriminative stimuli and reject the perspective (more close to methodological behavioral formulations) that private events do not affect public behavior at all. They argue that:

"if one subscribes to this perspective […] it would not be necessary to spend much time investigating the status or role of private events […] it seems unlikely that humans would acquire private behavior at all if it were not functional. Also, because pausing to think not only expends effort but also produces a delay in the reinforcers for overt behavior, thinking would not be maintained even if it were established temporarily. Thus, it sems likely that thinking does, at least some of the time, play an important role in the chain of behaviors" (p. 6).

This possible conceptual formulation of private events found in the behavior-analytic literature could be then one that considers private responses in the brain (as single synaptic events or cooperative synaptic events taking place in the cortical columns or macro-columns) as responsible for new stimulus conditions which acquire discriminative value in the brain environment. These new stimulus conditions are able to create links in behavioral chains, where a private event produces conditions in which other private or public responses are evoked. This conceptual formulation of private events is complementary to the one developed by the neurosciences and, therefore, is extremely interesting from an interpretative point of view and makes the development and extension of the actual analyses of complex neural systems possible.

A thorough analysis of private events in the science of behavior should probably focus also on conceptual issues like the interesting one brought to the reader's attention by Anderson et al. (2000). It concerns the lack of even a clear differentiation between private responses and private stimuli[15]. It is clear from this discussion that, even if there is consensus in the behavior-analytic community over the role played by private events in the emission of overt behavior, further empirical work and theoretical formulations are needed to advance the understanding and incorporate private events into behavioral science. That objective has of course to be pursued by relying on the basic principles of behavioral science and by staying conceptually systematic, to avoid the risk of turning to flawed analyses. But, in encouraging the community to find, through research and theoretical work, ways to develop an "integrated, natural science of behavior" (p. 9) which will impact the lives of not only typical developing people, the authors are actually stating the importance of finding a convergence with other disciplines that can provide a conceptual frame of reference and a set of technologies in which an analysis of private behavior can be performed, finally fulfilling Skinner's expectation about the topic. This approach could get us out from the loop of acknowledging the importance of private behavior but not including it in our conceptual analysis and applied work and could let us provide an area of convergence with sciences that have dedicated themselves to the study of private behavior emitted at neurological level, like neuroscience[16]. Also, a more thorough analysis of private behavior could improve and get behaviorism some tools for the analysis of private events like emotion, which could be an important element in some branches of behavior-analytic clinical practice. Again, it's not that behavior analysts do not consider emotion-related behavior important[17], it's that it's difficult to implement an analysis of emotion because it requires a specific set of knowledge that a perspective and a work on bridging the gap between behavior analysis and neuroscience could also bring.

Of course, the topic of a possible role of private events in the science of behavior has been fertile ground for further discussions in which also some form of disagreement has arisen. The first source of disagreement concerns the idea that a "molar" (Baum, 2011a, 2011b, Schlinger, 2011) approach to understanding behavior is just sufficient and that, even acknowledging their existence, it is not necessary to study private events in a science of human behavior, because these events occur on a "too small scale" that is not necessary to understand them (Schlinger, 2011). Some concerns, however, have been expressed towards

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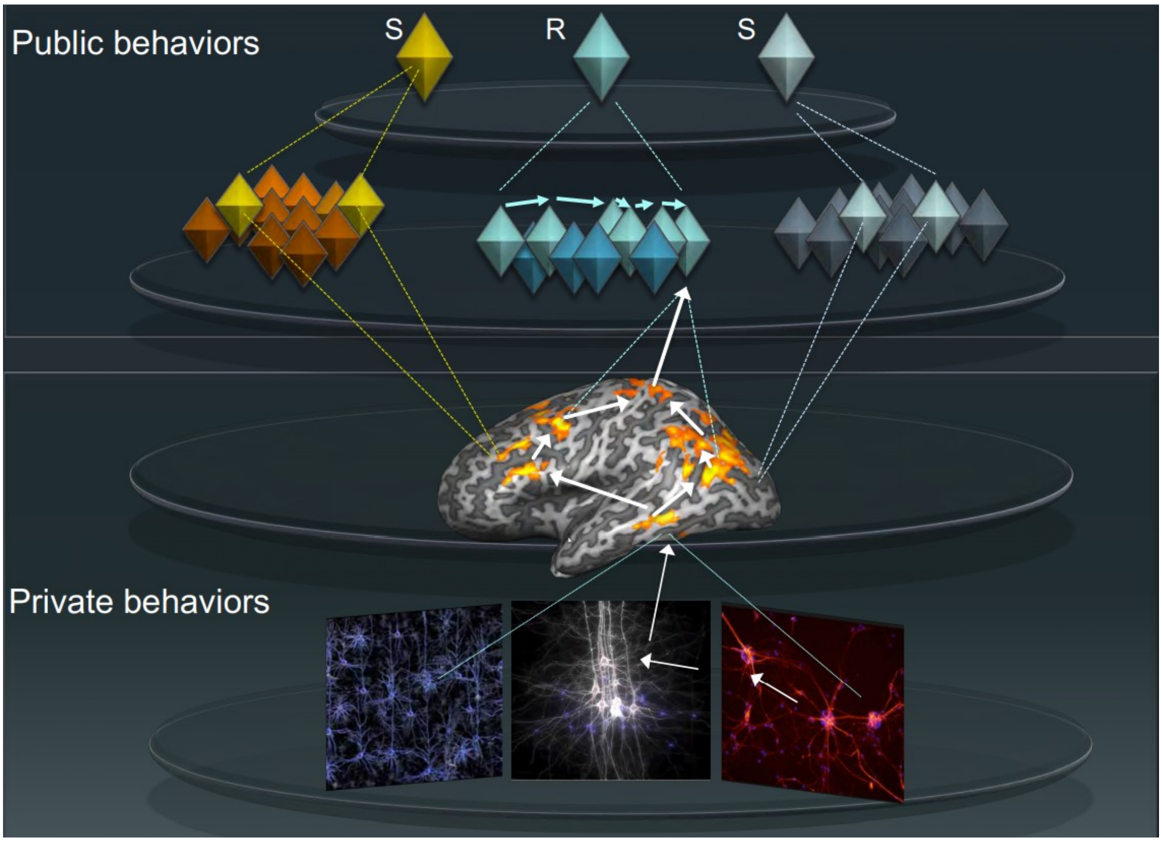
[15] The author state that behavior analysists "almost totally ignore all private events, not even differentiating between private responses and private stimuli"(p. 3).

[16] Private behavior in the form of neurological responses would not be then considered as a correlate of behavior, but as behavior itself.

[17] Yet, the risk for behavior analysis could be to stipulate that it does not focus its attention on respondent relations, or relying on an analysis with potentially serious weak points.

this "molar view of behavior" (Baum, 2011a) by authors like Palmer (2011), because although the behavior-analytic community has not reached a consensus about the topic (Palmer, 2004), the idea that a complete understanding of behavior must include also stimuli and responses that are unobserved is fairly widespread. The fact that they are unobserved, again, does not mean that they are not to be comprised in behavioral relations, and probably part of the problem lies on what the word *private* means for some behavior analysts. If private means *unobservable*, then a position like the one of Baum (2011a, 2011b) is understandable, but if *private* means *unobserved,* then the perspective is completely different and a "molar view of behavior" is more difficult to be agreed upon (Schlinger, 2011). Rather, the presence of different levels of complexity of analysis among which we can choose now or in the future is acknowledgeable. Like Schlinger (2011) points out, "many events in the history of science that were unobserved at one time were later observed with improvements in technology" (p. 183).

The following figure would provide a visual description of the different levels of complexity that an analysis of behavior, either at the private or the public level can embrace, and how our experimental analysis would probably constantly be applied to a "tiny fraction of natural phenomena, be it behavior or anything else" (Palmer et al., 2004), be it private or public behavior.



From: Di Salle, F. Ianniello, M., Pappalardo, E., *Modifying the Intraverbal Response through the "Crossword Effect" and Neuromodulation Techniques,* National Autism, Conference 2020, session # 34.

The figure depicts how a private event may be considered as a cooperative synaptic event occurring at the level of the cortical macro-columns, or at the level of the single columns, or even as a single synaptic event taking place at the level of the single neuron. But this would not be all about the issue of complexity: as the figure shows, even a publicly observable event taking the form of a stimulus or a response can be the result of multiple (possibly chained) other private or public events. By all means, the development of an integrating perspective encompassing "the observation of neural activity itself […] makes evident that many conceptualizations of public behavior are intrinsically incomplete, neglecting the complex private behavioral chains that make public behavior possible." (Pappalardo et al., 2019, p. 27).

1.5 Building a convergence by overcoming criticisms

As the two sciences developed independently from each other, they also built conceptual and methodological structures that may not be easily merged nor even made comparable at a first glance. The neurosciences in particular have produced an incredibly high number of scientific papers that focus on the study of brain processes and digging, as time went by, in more and more complex levels of analysis and methodologies. Let's think for example to the *Independent Component Analysis* (ICA), a data-driven method of analysis of fMRI data based on blind signal separation and on the assumed statistical independence of the source signal itself (McKeown et al., 2003). In fact, in an attempt to avoid complications in the proper interpretation of neural data and not to jeopardize the analysis of their relation to brain activation, neuroscience developed this data-mining approach, which allows to better isolate the signal of interest and better analyze task-related changes in fMRI data[18].

A first moment of shown interest in the study of the brain by the behavior-analytic community was represented by a series of published studies, aimed at opening to a more productive discussion on the topic. A paper published by Diego Zilio in 2016 was for instance aimed at pointing out that Skinner did not criticize neuroscience nor denied the relevant explanations of behavior that this science, as a non-mentalistic approach, can offer to the science of behavior, and that he considered neuroscience as "a field that could also present means for achieving more effective ways of prediction and control of behavior" (p. 198). He argued that recurring to an integrated behavior-analytic and neuroscientific approach does not necessarily mean for behavior analysis to be less conceptually systematic, as long as neural activity is considered, just as Skinner claimed, as behavior (neural behavior), and not a correlate of behavior, and as long as we perform a proper study of the nervous system and don't look "into the black box for the wrong things" (Skinner, 1969, p. 282). Moore (2002) wrote about *behavioral neuroscience* as an expression of a comprehensive science of behavior in which a full explanation can be provided about how organisms' behavior and neural systems are related to the environment and about the possible mediation roles played by any variable in this context. According to Moore (2002)[19], this "cooperative rather than competitive, mutually supportive rather than

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[18] As McKeown et al. (2003) point out, although being a non-invasive measure of brain activity, the blood oxygen level dependent (BLOD) signal in fMRI carries contributions from other physiological sources, related for example to the heart beat or to breathing, and also from other possible confounding variables, like head movements. These additional contributions make the isolation of the signal of interest a potential issue. That is why in fMRI experiments the signal extracted from a specific voxel when the volunteer is performing a particular task is compared to a baseline condition, which is, however, no different from the task condition in carrying cortical activity itself. For this reason, a more direct way of evaluating if a given voxel signal is actually affected by the given task execution is to cross-correlate it with a reference time course representing the sequence of the behavioral events expected in the experiment. The authors further note that, if correlation reflects a confirmatory analysis, explorative approaches aimed at uncovering the modulation of the data in an independent (not a priori) way can complement the hypothesis-driven methods and more effectively separate confounds.

[19] See also Donahoe, 1996.

mutually exclusive, […] reciprocal rather that restricting” (p. 274)[20] approach deals with how “neural and hormonal systems are changed by experience” (p. 262) and how these neural changes affect future behavioral responses. As Moore (2002), also Ortu and Vaidya (2016) wrote about a *behavior analytic neuroscience,* as part of a “boundary-breaking” scenario for behavior analysis to interpret neuroscientific data[21]. Interest in the acknowledgment of covert responding and in the identification of physiological structures that can mediate behavior is also shown in the analysis of listening and auditory imagining as operant behavior occurring at a covert level made by Schlinger (2008, 2015), which further contributes to dismiss any indication of dualistic perspective on cognitive events and physical events and opens to a study of behavior by two sciences at the same time. Schlinger (2015) then argues that behavior analysis conceptual and experimental framework can be used by neuroscientists to investigate behavior at the neural level without recurring to cognitive explanations.

Notwithstanding this first effort to create a cooperation ground between the two sciences, the study of the brain has remained a main topic of interest for disciplines other than behavior analysis, and so “its development has been mostly centered around research questions, conceptual frameworks, terminology and experimental designs a behavior analyst would not easily agree with, nor recognize as appropriate.” (Pappalardo et al., 2019). In addition, some forms of criticism have been raised by the same behavior analytic community towards functional neuroimaging methodology of analysis of neural data, specifically concerning the nature of the data themselves, the variability they intrinsically carry, the experimental designs used and the observation and “measurement” of the investigated phenomena. As a matter of fact, the criticisms reflected actual weak points of functional neuroimaging, but the evolution of neuroimaging procedures has overcome them in a way that is much more acceptable for behavior analysis. One basic revolutionary change in neuroimaging procedures has happened just recently and consists in a new modality of collecting data *in real time*, so looking at the brain activity just like we would

[20] For rich and compelling descriptions of the complementary nature of behavior analysis and neuroscience, see also Donahoe (2017) who provides a description of neurophysiological events related to behavior, such as reinforcement, stimulus control and memory.
[21] The authors argue that in this same scenario some measurement systems can be obtained and that they can be a tool at the disposal of the behavior analyst. For a specific focus, in the present work, on behavioral measures of brain activity, see Chapter 2.

look at other traditional dependent variables and is centered on the analysis of single trials in single volunteers, just as behavior analysis does.

When it comes to the nature of the data, the problem consists in the fact that data are only indirectly linked to neural activity, because what is actually measured are the hemodynamic changes accompanying brain activity. This, of course, does not jeopardize the dependability of the functional relation between the measure adopted and the brain activity itself, provided brain activity and hemodynamics are dependably linked to each other. Otherwise, the publication of such a great amount of scientific papers in the field of neuroscience would not have been possible. From a behavior analytic point of view, though, this appears as an indirect system of measurement, making use of arbitrary units (% signal variation with respect to baseline). A way to overcome the problem is placing the real focus on the signal changes and not on the absolute value of the hemodynamics.

Another criticism concerns the high intra- and inter- individual variability of the data related to brain activity and the common practice in neuroscience to flatten this variability through the averaging of multiple trials and multiple subjects. One of the reasons why this kind of averaging processes have been used by neuroscience is that it allowed to eliminate from data a particular set of confounding variables defined "noise". The most modern technologies used by functional neuroimaging have finally increased the signal to noise ratio of measures and have so managed to eliminate the noise reduction purpose of averaging thus allowing the focus to be placed on the single trial and on the single volunteer. If not for this procedural problem, the high variability of data should not be a concern for the behavior analyst, who should be more than other scientists accustomed to take variability into account and to actually explore its sources. There is no reason why variability characterizing public behavior should not be parallel in the brain environment, or even be enhanced by the complexity of brain-environment relations. Of course, solving the problem of variability has also allowed not to ignore the study of all the possible concurrent independent variables influencing neural functioning, and the use of single subject designs is just more acceptable for the behavior analytic community than group studies.

The issue of deactivation (i.e. negative changes of brain activity), instead, needs to be addressed as a neural phenomenon that has no exact parallels in the realm of publicly observable behavior. What we can say about public behavior is if it is occurring or if it is not occurring, meaning that we are able to detect the presence of an overt response or not. Deactivation can be difficult to translate in behavioral terms, because it implies that the opposite of activity would not consist anymore in the absence of activity, but instead in a new condition of negative activity, which is not the same thing as the absence of a response. The answer to this criticism simply consists in that some neural phenomena do not have easy parallels in the behavioral sciences. Neural activity needs to include both an increase (activation) and a reduction (deactivation) in firing, because otherwise they would compete with each other for common resources (Di Salle et al., National Autism Conference, 2020).

The possible criticisms related to the use of inferences in neuroscience, and specifically regarding the use of temporal correlations to infer that a stimulus has a functional role, is to be addressed as not contrasting with, for example, the role of SDs, which are antecedent stimuli thought to have an evocative power on behavior, provided they are temporally correlated to the emission of a response and with the availability of reinforcement (Pappalardo et al., 2019). In the same way, in functional neuroimaging it is possible to formulate "predictors" of neural activity based on an inference of their evocative power on the response and to then "extract *stimulus-correlated* neural activity from the full dimensionality of fMRI data." (Pappalardo et al., 2019). Inference, anyway, plays a much more influent role on our knowledge of the world than we probably realize, as this knowledge is "built upon what we already know" (Pappalardo et al., 2019, p. 25). Tons of example of inferences in our daily life can be made: anytime we need to name an object we could do it based on inferences related to its similarity with objects pertaining to the same category as the "unknown" one. In the study of neural activity related to visual perception and imagination (Trojano et al., 2000; Klein et al., 2000), it has been found that there is a specific convergence of their neural pathways and they share a common neural basis. If when perceiving the activation of imaginative areas is involved and, when imagining, perception at the private level occurs anyway, this makes imaginative activity actually what Skinner called "seeing in the absence of the thing seen" (1974) and makes of the perception, the "knowledge of the world", a process of reference to what we have already perceived in the past, as in a matching to sample task to other stimuli which have already been established in a particular stimulus class. It has been shown (Goebel, 1998) that the human brain can tend to function based on what it expects, thus demonstrating the constructive nature of perception.

All the considerations made can play a pivotal role for creating the right ground for two scientific communities to start a dialogue after so many years spent without taking advantage of each other's research. The perspective of a dialogue between neuroscience and behavior analysis brings a potential chance of conceptual advancement and overall improvement for both disciplines. Of course, an ongoing interface and a continuous work of translation of conceptual frameworks and methodological approaches are needed to keep the dialogue open and to make it more and more fructuous.

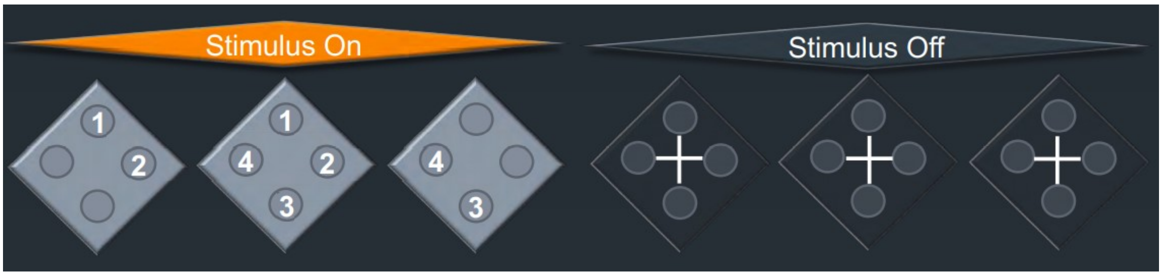
CHAPTER 2

MAKING PRIVATE EVENTS PUBLIC BY FINDING CORRESPONDING MEASURES OF COVERT AND OVERT BEHAVIOR

2.1 Study 1: Brain Responses Measured Through the Continuous Measures of Behavior

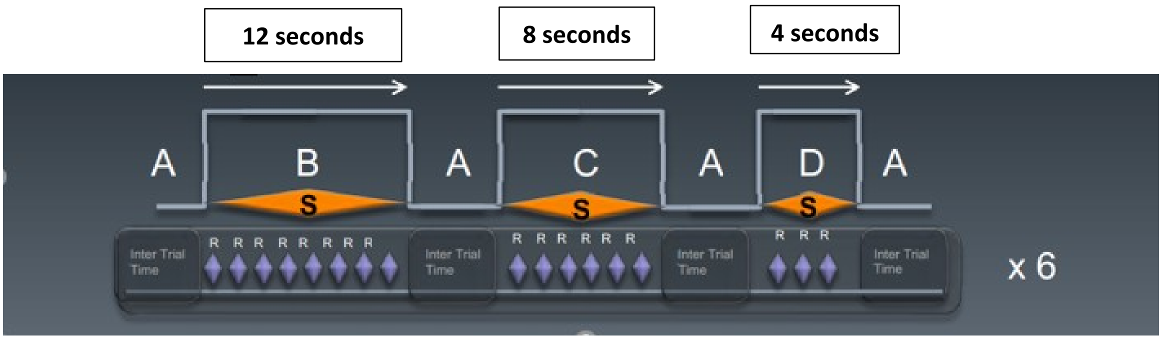
The first step in bridging the gap between behavior analysis and neuroscience would be digging in a new level of analysis which provides the possibility of identifying physical events in the brain and thus making private behavior public. It took the form of a neuroimaging experiment in which brain responses subserving the behavior of moving a finger were measured. The experiment allowed to single out the brain area in which the private part of the target behavior, a "single neural episode" (Pappalardo et al., 2019), was emitted, and, more importantly, to analyze the correspondence of continuous measures of behavior in its private and public occurrence. The experiment was performed in a single volunteer, to match one of the methodological features and encounter common practice of both basic and applied research in behavior analysis. It aimed at answering a series of experimental questions, and specifically if we can be able to study brain activity as to isolate and recognize physical neural events, and if, in that same context, we can finally set the occasion for two different observers to agree on the same "mental" event (Pappalardo et al., 2019).

The task performed by the volunteer was composed by a series of "motor activity trials", in which a visual stimulus was present to signal the duration of the independent variable periods, the ones in which the volunteer was required to move their finger (and which finger to move). In the baseline condition, by contrast, the visual stimulus was replaced by a fixation cross and no finger moving response was required. See the following figure for a visual representation of the experimental protocol:



From: Di Salle, F. Ianniello, M., Pappalardo, E., *Modifying the Intraverbal Response through the "Crossword Effect" and Neuromodulation Techniques,* National Autism, Conference 2020, session # 34.

The duration of trials was randomly varied from 4 to 8 and to 12 seconds, each condition was repeated 6 times, and the temporal resolution of the experiment was 2 seconds:



Adapted from: Di Salle, F. Ianniello, M., Pappalardo, E., *Modifying the Intraverbal Response through the "Crossword Effect" and Neuromodulation Techniques,* National Autism, Conference 2020, session # 34.

The experimental design used was conceptually a "reversal/withdrawal", with many applications and withdrawals of the independent variable. In behavior analysis, reversal designs are experimental designs in which the demonstration of the internal validity is reached by "reversing" responding to a level obtained in a previous condition (Cooper, Heron, & Heward, 2020) by, for example, withdrawing the independent variable, and their conceptual equivalent in neuroscience are very common for the acquisition of neuroimaging data. The use of such an experimental design highlights an important point regarding the convergence of the two sciences and will be further discussed in the present work[22].

Identification of the topographical correspondence between private and public behavior

From the perspective of a science of behavior integrating the study of the private neural responses accompanying the publicly observable ones, the importance of this experiment is represented by the possibility to single out the brain areas in which the private behavior subserving the public motor response was emitted:

[22] See Chapter 4, also for further discussion on how the methodological features of an fMRI experiment and data processing can be embedded in an conceptual behavior analytic and neuroscientific, integrated frame of reference.

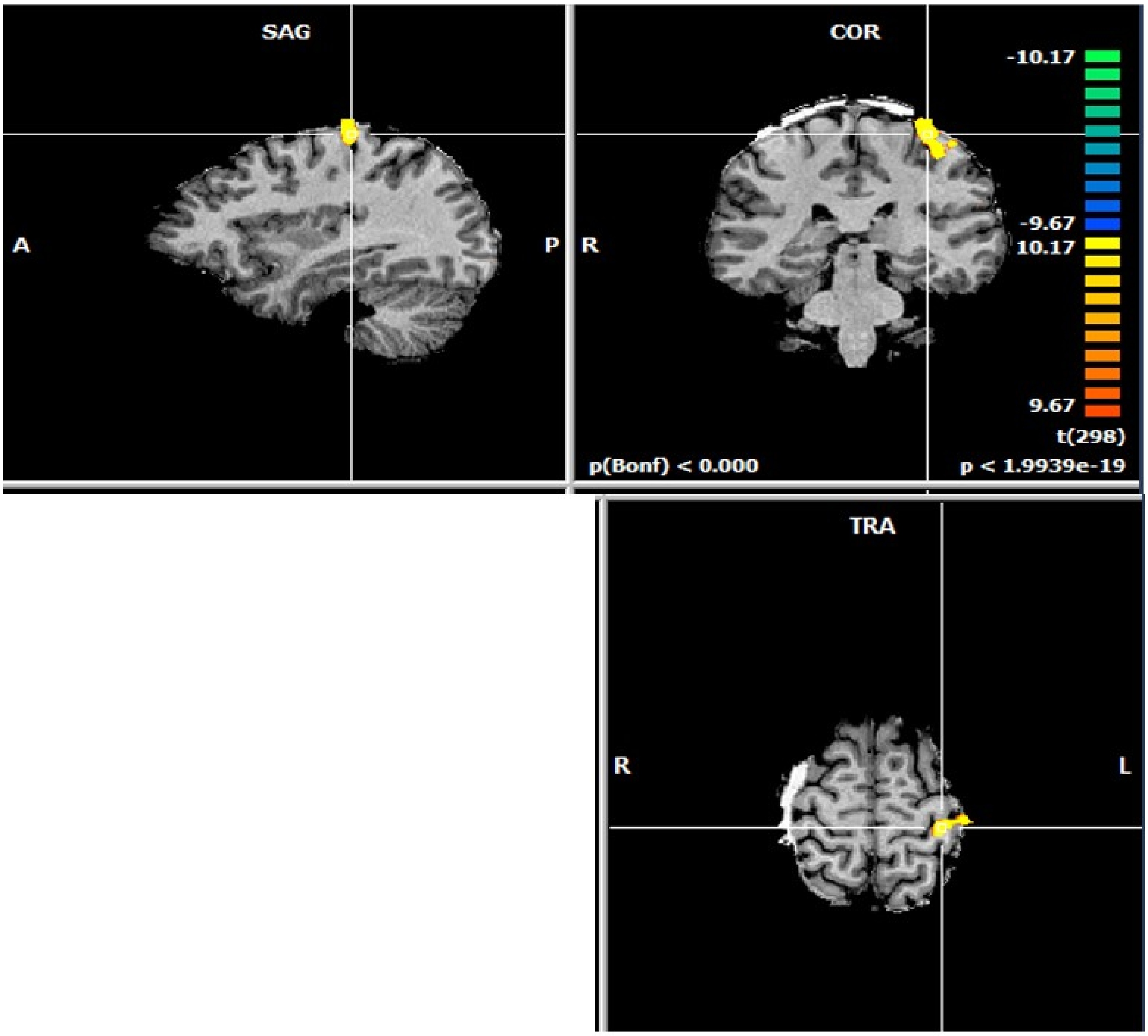


Fig. 1. Representation of the neural activity detected in the Primary Motor Cortex during the performance of a finger movement behavior.

so to observe it and meet Skinner's requirement that a science of the nervous system must directly observe neural processes. Identifying anatomically the brain area in which the private behavior is emitted is an equivalent of a behavioral definition of the form (topography) of the neural response. In fact, a brain area can be defined as a region in the brain cortex having homogeneous cortical architecture and being responsible for the emission of responses pertaining to a formally similar group (topographical response class), even though a very generic one (i.e. moving any part of the body). If topography in the brain refers to the pure anatomy of cortical structures, the showed activation of the Primary Motor Cortex in correspondence with the emission of a public motor response shows the neural topography corresponding to it. A brain area can be also correlated to a particular cortical function, but this is instead a matter of specificity of the particular categories of stimuli which selectively reach that determined area.

Measuring single instances of the private responses

The experiment also shows that it is possible to find a correspondence between public and private responses, which are perfectly measurable in the single episodes, thus placing neural behavior at the very same level of its overt counterpart.

Count measures

In the following figure, it is possible to observe the correspondence between the two classes of responses, that's to say the occurrence of the public (represented in color bars) and the private motor behavior (represented by a data path of 300 data points with the temporal resolution of 2 seconds). The figure is a representation of the neural activity along time (time course) in a particular brain region of interest (ROI) and shows how the single motor public and private episodes can be studied together, thus offering a first representation of the convergence of private and public instances of the target (finger moving) behavior:

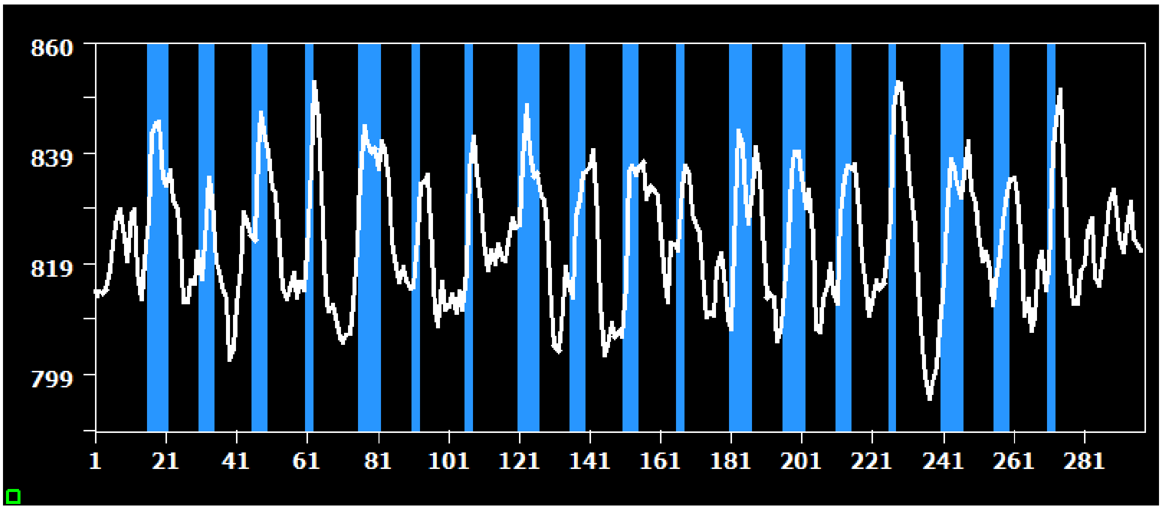
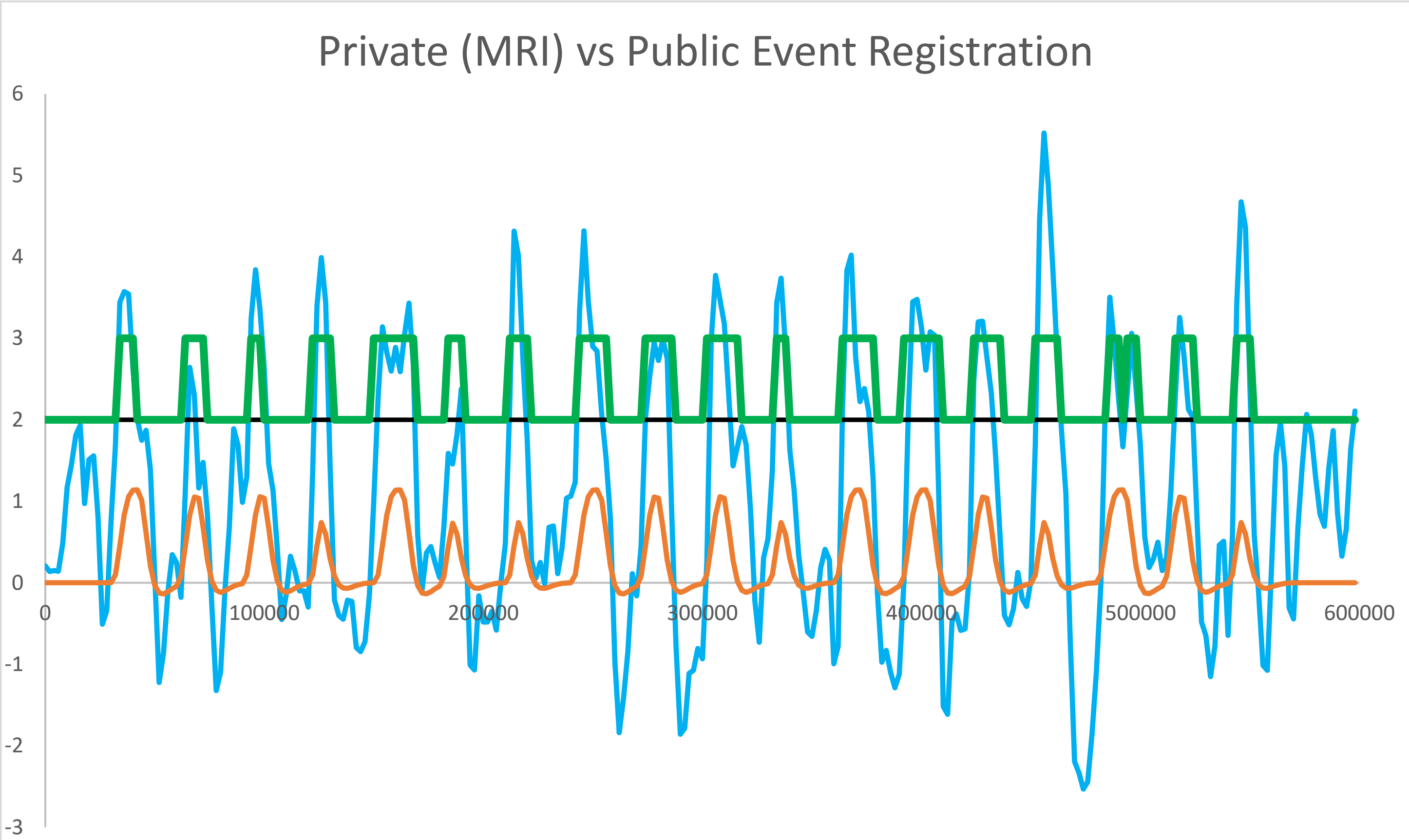


Fig. 2. Representation of the correspondence between "neural motor episodes" (colored bars) and "public motor episodes" (white data path)

This convergence is also represented in the following graph, which shows the detection of the occurrences (*count measure*) of the target behavior in the Primary Motor Cortex and in the "public realm", and can be clearly verified in the correspondence of the events detected in the time course (green data path) above a "threshold of observability" and the public behavior of the volunteer, that produces a representation of the expected neural activity (the *predictor* - orange data path)[23]:



A further element of "believability" for this correspondence can be represented by a common behavior analytic indicator of measurement quality (Cooper, Heron, & Heward, 2020) called Interobserver Agreement (IOA), and used in behavior analysis to determine the degree to which two different (and independent) observers report on the same observed and measured event. It is expressed in the form of a percent of agreement between the "two observers" (i.e. a public observer of the public finger moving behavior and the private neural activity related to it and represented by the time course) and is considered acceptable if it achieves no less than 80%:

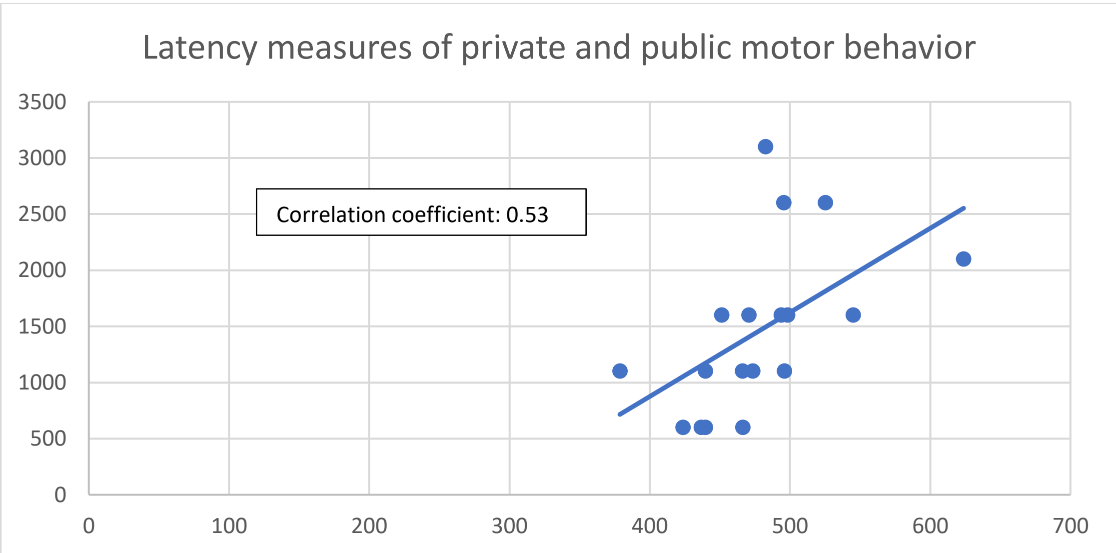
[23] A *predictor* can be considered as the result of a convolution of the expected neural activity with the hemodynamic function. For further discussion about this topic and about the need to establish a "threshold of observability", see Chapter 4.

"OBSERVERS"	NUMBER OF EVENTS REGISTERED (COUNT)	TOTAL COUNT IOA
Time course	19	94,7%
Public observer	18	

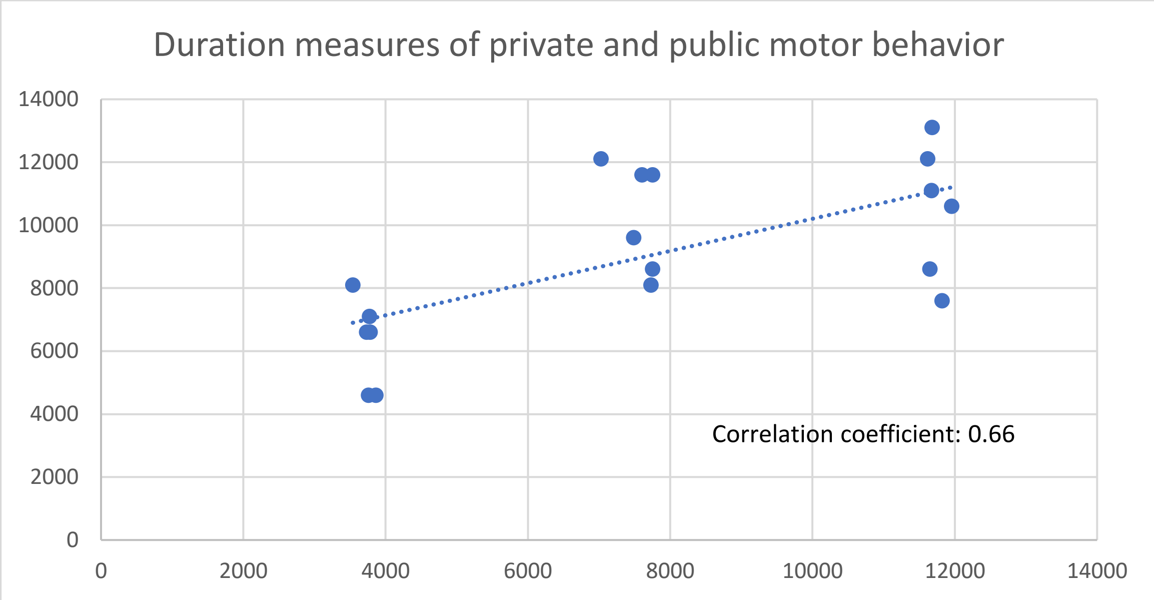
Among other purposes, IOA is used in behavior analysis to increase the confidence that the definition of the target behavior, in our experiment at both private and public levels, is clear. It can be thus considered as a further confirmation of the possibility of a high degree of correspondence between private and public events.

Duration and latency measures

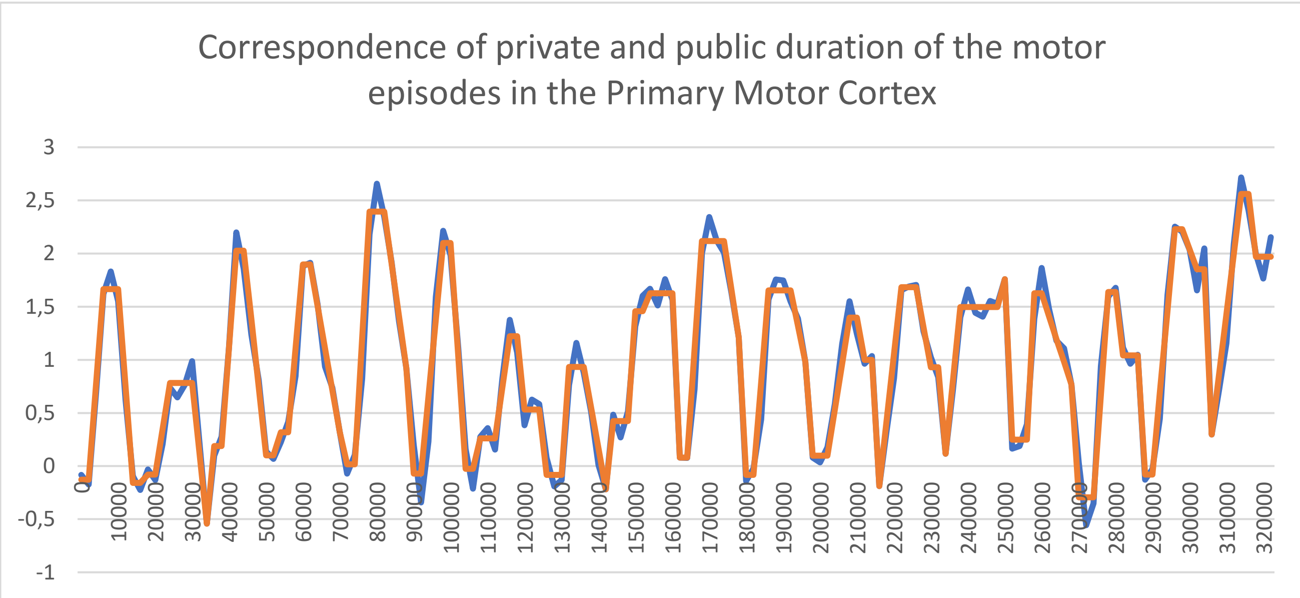
The following section describes how other measures of the single motor public and private episodes were possible and that a correspondence between some other dimensional quantities of the public and the private responses can be found. In particular, latency measures (i.e., measures of the elapsed time from the onset of each stimulus and the initiation of the response) in the Primary Motor Cortex were taken for the publicly observable motor responses (the ones registered from the volunteer's finger tapping) and the neural time course (with a temporal resolution of 500 milliseconds):



The different width of the color bars depicted in Fig. 2 represents different durations of the "public motor episodes", so allowing a measure of the correspondence of private and public behavior not only at the level of a count of episodes, but also of their duration (with a temporal resolution of 500 millisecond), as the following graph shows:



As for the count measure, also for the duration the correspondence of the private and public responses in a specific region of interest in the Primary Motor Cortex (with a temporal resolution of 2 seconds) can be shown:



SECTION II: FUNCTIONAL STUDY OF THE PATTERNS OF NEURAL ACTIVITY ASSOCIATED WITH THE VERBAL OPERANTS

CHAPTER 3

THE BEHAVIORAL CONCEPTUALIZATION OF LANGUAGE

3.1 Introduction

In 1957 B.F. Skinner published the book *Verbal Behavior*, in which he presented a detailed behavioral analysis and behavioral conceptualization of language. In this book, Skinner provided a definition for verbal behavior as behavior that is reinforced through the mediation of other persons – whereas non-verbal behavior is reinforced through the physical environment- and that for its "so may distinguishing dynamic and topographical properties" is entitled to be considered as a special kind of behavior (Skinner, 1957, p. 2). Skinner prefers the term "verbal behavior", instead of "language" or "speech", since this term draws the attention towards the specific individual producing a determined verbal response and, more importantly, "specifies (language) as a behavior shaped and maintained by mediating consequences" (Skinner, 1957, p. 2). A new term is then what best suits to mark a difference between the behavioral analysis to language and any other attempt in that sense which has not been ruled by an environmental explanation of linguistic phenomena, namely the formal linguistics model provided by Chomsky.

Even though Skinner's book did not contain any *experimental research* on Verbal Behavior, Skinner's work has impacted tremendously research and practice in the science of behavior (Sautter & LeBlanc, 2006). His analysis of Verbal Behavior has proved to be particularly important to the designing and implementation of behavioral interventions for individuals with autism spectrum disorder, since language and communication deficits are the core of ASD. The fact that the literature on specific teaching strategies and techniques has revealed itself to be influenced, consistent with and based on Skinner's *Verbal Behavior* further proves the enormous utility of his revolutionary conceptualization of language.

3.2 The "Functional Analysis of Verbal Behavior" and the Verbal Operants

Skinner's analysis (1957) focuses on the response *function*, that's to look at single utterances as the product of the antecedent environmental events that proceed them and as the result of the stimulus changes that follow it, rather than on the response form, whose specific name in behavior analysis is *topography*. Viewing the communication exchanges of a determined verbal community in this way, a single word (single response topography) can have as many functions as are the environmental variables that can operate in each instance: an antecedent stimulus condition corresponding to not having had drinks for a while could determine the emission of the word "water" to obtain water, while simply seeing water in a fountain could be responsible for the child saying "water" to share this experience with a significant other (i.e., a parent or a sibling). Skinner's point is that, although in the traditional grammar it may be considered as a unit of analysis carrying meaning, the word is not a functional unit, in fact a same word can carry different information on the verbal behavior of an individual speaker, depending on the environmental events that have occurred before and after it (Sundberg & Michael, 2001).

According to Skinner's (1957) classification of language, the *verbal operant* is identified as the elemental unit for the analysis of verbal behavior and each verbal operant is functionally defined by its relevant sources of stimulus control. Skinner argues that "the understanding of verbal behavior is something more than the use of a consistent vocabulary with which specific instances may be described": when we think of a specific verbal utterance, we cannot think of a word which is stored in our brain, but we must take into account the functional analysis related to its emission, in other words analyze the specific stimuli that exert control on that particular response. As discussed previously, instead of a classification by the form of the response, Skinner's classification is based on the functional relationships between stimuli and responses, so that a single word can be uttered in different verbal operants – under different antecedent and consequent stimulus conditions. He identified and named the following types of primary verbal operants: *mand*, *tact*, *echoic*, *intraverbal*, *textual*, and *transcription* (he described two kinds of transcriptive behavior, which he called *taking dictation*, and *copying a text*)[24].

[24] Skinner also identified a secondary verbal operant, the *autoclitic,* whose detailed description goes beyond the scope of the present work.

The first verbal operant described by Skinner is the *mand*. The mand is a verbal operant controlled by a particular condition of deprivation or aversive stimulation and that is reinforced by a specific consequence. There is no specific relation between the antecedent stimulus and the response product, but there *does* exist a relation between the response topography and the reinforcement provided by the verbal community as a consequence of that particular instance of mand behavior. An example of mand can be a child requesting a particular toy to his mother by saying its name ("Truck") and his mother delivering to him that specific toy (the mother gives the child the truck).

If the mand is the one verbal operant which falls under the control of a particular condition of deprivation of the consequence specified by the response topography, or of some kind of aversive stimulation whose termination is the aim of the production of the mand itself, *echoic*, *textual* and *intraverbal* operants are, according to Skinner's conceptualization, instead under the control of verbal antecedent stimuli. Skinner defines the echoic as a verbal operant evoked by a verbal stimulus which has point to point correspondence and formal similarity with the response product and for which the reinforcement is nonspecific to the response topography. Echoic behavior tends to appear fairly early in typically developing children (Sundberg, 2008), and it soon becomes an important pre-requisite, if not a fundamental repertoire, for the development of other forms of verbal behavior (Skinner, 1957).

Like the echoic behavior, also the textual operant is evoked by a verbal stimulus that has point-to-point correspondence with the response topography and is maintained by generalized conditioned reinforcement, but in the textual operant there is no formal similarity between the antecedent stimulus and the response product. In other words, when we read a word from a book, that word coming as a visual verbal stimulus, the product of the reading (textual) response has point to point correspondence with the stimulus, but has at the same time an auditory nature, thus not formally similar to the nature of the stimulus evoking that same response.

Other two operant classes defined by Skinner and sharing with the textual operant the visual nature of the antecedent verbal stimuli are the ones grouped under the name of *transcription*, and that need to be considered because verbal behavior is not always vocal, but it can be also written instead. In the paragraph dedicated to transcription in his book (1957), Skinner writes about *copying a text* and *taking dictation*. Copying a text is verbal behavior evoked by a written verbal stimulus which has point to point correspondence and formal similarity with the response product, i.e. the responses product has a visual nature. When a vocal verbal stimulus controls a written response, instead, we are in front of a taking dictation response, as in for example the behavior of a student taking written notes out of a lecture.

Intraverbal responses, as Skinner defines them, are also evoked by a verbal stimulus, but there is no point-to-point correspondence between the stimulus and the response product nor necessarily formal similarity and, once again, the reinforcement is nonspecific. Skinner provides several examples of intraverbal, and even extends its discussion to special cases of intraverbal behavior, as for example translation. It will be discussed later in this thesis that the definition of intraverbal provided by Skinner can be different, essentially simpler, with respect to some other kind of related phenomena involving the effect of a verbal antecedent on a verbal response (Palmer, 2016).

The *tact* operant is similar to the echoic, the textual and the intraverbal because of the presence of a discriminative stimulus and because it is established by generalized reinforcement, but the discriminative stimulus evoking the tact response is a nonverbal stimulus. Skinner defines a tact as a verbal operant in which the response is “evoked (or at least strengthened) by a particular object or event or property of an object or event” (Skinner, 1957, p.82). As for the echoic, the textual and the intraverbal behavior, also for the tact “the only useful functional relation is expressed in the statement that the presence of a given stimulus raises the probability of occurrence of a given form of response” (p.82). As Sundberg (2015) notes, the unique type of stimulus control it has and the influence it can exert on the acquisition of other types of verbal behavior led Skinner to consider the tact as the most important of verbal operants (Skinner, 1957). In fact, the acquisition of a strong tact repertoire corresponding to be able to “talk about” the physical environment (the constellation of nonverbal stimuli acquiring control over the tact responses) when it is present is an important prerequisite to transfer this kind of skills to other types of verbal behavior that can depend on it.

3.3 The Functional Independence of Verbal Operants

We have seen how, in contrast with the traditional linguistic conceptualization of language which centers around “meaning” and assumes that once the “meaning” of a word has been acquired by a determined speaker, they will be able to use the word no matter what the specific conditions are, Skinner's conceptualization of language considers each operant as the product of the relevant environmental variables (Skinner, 1957; Sautter & LeBlanc, 2006) and as an independent unit for an analysis of language that, thus, has to be accounted separately:

"In the terminology of meaning, we say that the word *doll* is used at one time "to ask for a doll" and at another "to describe or refer to a doll." When the response *Doll*! has been acquired as a mand, however, we do not expect that the child then spontaneously possesses a corresponding tact of similar form. If we find both types of operants in the repertoire of the child, we must account for them separately. This appears to make the task of explaining verbal behavior more difficult, but the advantage which appears to be gained by the traditional concept of the "word *doll*" is offset by the problem which remains of explaining how a child may learn to use a word both to "express a desire" and also to "describe an object." The total formulation has not been simplified; part of the task has merely been postponed. If we are to accept the full responsibility of giving an account of verbal behavior, we must face the fact that the mand *doll* and the tact *doll* involve separate functional relations which can be explained only by discovering all relevant variables." (Skinner, 1957, pp. 187-188).[25]

The behavior analytic literature has clearly shown that an experimental analysis of verbal behavior and of the presence of independent functional control has successfully followed Skinner's *Verbal Behavior* and whose utility for prediction and control seems evident especially for developing training intervention for individuals with language delays (Fryling, 2017; Petursdottir & Devine, 2017; Sautter & LeBlanc, 2006; DeSouza et al., 2017). This research has supported such a central feature of Skinner's analysis of verbal behavior by focusing on the direct training of one verbal operant and then on probing other verbal operants "to see if responding would spontaneously emerge" (Sautter and LeBlanc, 2006, p. 42). The authors point out that "the results almost always demonstrated that the participants who were taught one specific operant did not spontaneously demonstrate the emergence of other untrained operants. Thus, the development of a functional communicative repertoire required direct intervention for each operant" (Sautter and LeBlanc, 2006, p. 42).

[25] See also Sundberg & Michael (2001).

However, as Sundberg & Michael (2001) note, Skinner acknowledged the fact that a sophisticated speaker can acquire a functional relation of one form, (i.e., a response topography in one operant), and then be able to use it under different environmental circumstances (i.e., in another operant) without specific training (p. 704). The authors argue that “this seemingly spontaneous transfer from one verbal operant to another also needs analysis in terms of basic behavioral concepts and principles and in some cases turns out to be quite complex” (p. 704). They note that Skinner’s *Verbal Behavior* provides so many relevant points at this referral to develop teaching strategies for verbal behavior and not to underestimate either the potential complexity of the issue or the need to a more complete behavioral analysis of it (p. 705). As Fryling (2017) suggests, a lot of examples can be found in our day-to-day life. Think about learning a second language: in most cases, learning an intraverbal response may lead to manding for the item without specific training. As a matter of fact, behavior analytic research literature has also shown that verbal operants may be functionally “interdependent” also for individuals with disabilities. (See Sautter & LeBlanc, 2006 and Fryling, 2017 for further discussions on the topic).

3.4 The Multiple Control of Verbal Behavior

A fair way to summarize the whole point is stating that verbal operants are considered to be functionally independent, but they are also interrelated or can be so through the use of stimulus control transfer procedures (Sautter & LeBlanc, 2006). As Michael, Palmer, & Sundberg (2011) note:

“The purpose of Skinner’s analysis was not to provide a classificatory scheme into which examples of verbal behavior can be assigned but to identify the controlling variables that are responsible for them. The elementary verbal operants exemplify each type of control, but verbal behavior is typically determined by many variables operating concurrently, with effects sometimes supplementing and sometimes competing with one another” (p. 19)[26].

In their article on the multiple control of verbal behavior, the authors summarize Skinner’s discussion on “Multiple Causation” (Skinner, 1957) and provide a new terminology for multiple control of verbal behavior. Michael, Palmer, & Sundberg (2011) note that multiple control is “the rule rather than the exception” and point out that for practical and applied purposes we operate some form of simplification of the contingencies that operate on each

[26] The authors suggest to see also Palmer (2009).

verbal response we emit by arbitrarily determining the dominance of a particular contingency over potential different others. In fact, they argue that outside of the laboratory -where it is easier to isolate "pure" verbal responses- in the day-to-day life our verbal behavior is the result of a series of interacting variables. In what they call *divergent multiple control*, "a single variable controls a variety of responses" (p. 7) that result to be incompatible with each other, but that change in strength and could be potentially emitted. In such cases, the stronger response emerges, and that is because of that particular speaker's history of reinforcement or "because of the confluence of other evocative variables at the moment" (p. 7)[27].

The article also provides the term *convergent multiple control* for when "more than one variable strengthens a response of a single topography" (p. 5), for example a child requesting for a present item. In this particular condition, it is not easy to determine if the operant emitted is a "pure mand" or a "pure tact".

Therefore, it is important to acknowledge the simplification we make of the very complex variables that modulate the emission of verbal behavior under natural circumstances.

[27] Once again, the authors recommend to see Palmer, 2009, for a further discussion concerning this topic.

CHAPTER 4

STUDY 2: DEFINITION OF THE “NEURAL FINGERPRINTS” OF THE VERBAL OPERANTS

4.1 Introduction

The purpose of Study 2 is to provide a neural definition of the verbal operants, so to create their *neural fingerprints* by singling out the specific patterns of neural activity related to their emission. To this purpose, the neural patterns subserving four primary verbal operants have been investigated in terms of the amount and of the spatial distribution of neural resources used to emit a particular verbal response. The functional Magnetic Resonance (fMRI) experiment conducted has displayed brain activity related to verbal operants in four neurotypical adult volunteers, reproducing the natural sources of control for each operant, and was aimed at a) singling out the brain area(s) where the neural behavior subserving the emission of verbal operants takes place, b) investigating the relative amount of neural resources a given verbal operant uses compared to the other operants, c) providing specific patterns of neural activity related to each verbal operant, as the convergence of the information in a) and b).

The conceptual and philosophical framework for the experiment has been described in the previous sections of this work, and it deals with neurosciences finally providing tools to observe the neural activity subserving public behavior and to understand the neural mechanisms underlying the emission of overt responses, thus contributing to create an integrated yet radical behavioral perspective linking public to private behavior.

The patterns of neural activity of each operant were expected to include specific brain regions (i.e., not activated by the other operants) and overlapping ones (i.e., activated also by the other operants). Showing that the emission of each verbal operant is associated to a unique pattern of neural activity, while single pattern components can still overlap, can be of significant conceptual and practical interest for the science of behavior. The unicity of each pattern can explain and show the neural underpinning of the functional independence of verbal operants, while the patterns’ overlapping components are likely to represent the neural basis for the multiple control of verbal behavior. In fact, a further analysis of both overlapping and differentiated neural loci for verbal operants was thought to contain fine-grained information about the differential use of neural resources related to the sources of control of each operant, and to explain how multiple control and functional independence of verbal operants are strongly grounded in the organization of verbal behavior at the neural level. In a way, the shown efficacy of transfer of stimulus control procedures in developing multiple verbal operants confirms that functional independence and multiple control do not necessarily have to be dichotomic. Nor the functional interdependence of verbal operants must threaten the value of Skinner's functional taxonomy of verbal behavior. If the lack of functional interdependence were to be considered as a behavioral-developmental problem, Skinner's taxonomy could be the basis for the assessment of "behavioral-developmental stimulus control problems and targets for intervention" (Fryling, 2017, p. 76 – see also Sundberg, 2008).

The experiment focused on the echoic, tact, intraverbal and textual operants. The reason why the other verbal operants were not involved is mainly due to technical limitations posed by the particular environment in which the experiment was carried out. In particular, the functional resonance environment would have narrowed the possible array of reinforcers to be managed by the experimenter and necessary for the implementation of mand training trials in such an environment, nor would have let the experimenter successfully spot the exact moments in which an establishing operation would be in place. What's more, it would have been more difficult to evoke a mand in the same way the other verbal operants were evoked in the magnetic resonance setting, for such an environment is particularly poor of discriminative stimuli for the availability of reinforcement. In other words, even if an MO had been present in a particular moment, it could not have been sufficient to evoke a mand in an environment in which no SDs for reinforcement may be present.

4.2 Methods, Data Collection and Experimental Design

The participants in the study were normal, verbally competent adults. Imaging data were collected using a 3-Tesla Scanner. The different stimulus conditions of the experiment were presented to the volunteers in the form of scenarios created by the experimenters and containing the stimuli to be presented with the precise timing required.

For each participant the experiment consisted of one fMRI session which lasted 25 minutes. There were 8 different stimulus conditions presented which were repeated 9 times each in an interspersed and random fashion, with a 20 seconds return to baseline in between each presentation of a condition and the following.

A short pre-experiment training was implemented with a different set of stimuli than the ones used in the actual experiment, allowing the participants to become familiar with the magnetic resonance setting, which requires the volunteer to stay still and to reduce to the bare minimum any kind of movements, included mouth and tongue ones. These movements, if present, would be captured as “noise” in the temporal series of images registered by the scanner.

The dependent variable measured corresponded to the neural response and consisted in a point-by-point (voxelwise) measurement of % signal variation during the emission of the target (vocal verbal) responses. The overt responses were also registered and used to validate the neural ones. After joining clusters anatomically located within the same brain lobe (i.e. occipital, parietal, temporal, frontal), the amount of neural activation (total number of voxels) in each lobe was calculated.

The independent variable consisted in the presentation of the antecedent stimuli specific to each operant studied. During the echoic condition, the participants were asked to repeat a single word provided by a pre-recorded stimulus from the software scenario. The verbal auditory stimulus provided was composed by an instruction to repeat immediately followed by the word to repeat.

During the textual condition, the volunteer was given an auditory instruction with which they were asked to read aloud a written word provided by the software scenario at the center of a black screen. The stimulus conditions corresponding to the echoic and the textual operants were composed of both “sense” and “nonsense” verbal stimuli (Italian words). The nonsense words were sequences of letters, and their inclusion in the experiment procedure determined a way to study these operants in their more “pure” nature, reducing the possible risk of the emission of private multiply controlled operants (echoic-tacts, echoic-intraverbals, textual-tacts, textual-intraverbals) along with the public verbal response.

During the tact condition, the volunteer was provided with a verbal stimulus (“What is it?”) and was asked to say aloud the name of a pictured object or of a sound in the form of a single word.

In the intraverbal condition the volunteer was given the instruction “Associate” and was asked to produce a single word association to a verbal stimulus that was provided in visual (textual) or auditory form. The tact and intraverbal conditions were designed to have both visual and auditory antecedents to set the occasion to study each of the two operants in an independent way from the physical nature of the controlling antecedent stimulus.

Once again, the experimental design used is conceptually a reversal/withdrawal design, in which there were several (72) applications and withdrawals of the independent variable. The data pertaining to each subject were analyzed individually, as a single subject study, but were also combined together in a second level analysis to enhance internal validity. There is a particular reason why so many applications and withdrawals of the independent variable and a second level group analysis of the four volunteers were meaningful for the experiment. As Skinner expected that bridging the gap between physiology and behaviorism would produce "more behavior to be explained" (1974, p. 115), studying neural behavior brings the analysis on a more complex level due to the intimate nature of the neural environment where a concept as simple as the "absence" of activity does not probably exist. In fact, neural activity is to be considered as a dynamic process, in which every region takes continuously part into neural assemblies acting chorally as functional patterns and dynamically varying following the specific features of the stimulation. The nature of the stimulation itself can also be complex: it can be a composition of public and private stimuli acting as the antecedents and as the consequences (largely automatic) to the neural behavior. It is necessary to compensate for possible confounding variables represented by unpredictable brain activity in the baseline, resulting from the volunteer engaging in the very same target response at the private level even in a baseline condition. Still, the particular methodological features of fMRI experiments, which comprise the type of experimental design, may not be enough to resolve the problem, for it is not possible to manipulate the brain in an "on-off" fashion as it could be certainly more easily done in the domain of public behavior[28]. When studying public behavior, it is possible to better control for confounding variables and inhibit accessory responses, as well as conduct baseline sessions with a relatively fair certainty that the relevant independent variables are not in action. In an experiment involving the analysis of neural behavior, then, performing several reversals can be the best way to protect the data from the inherent complexity of the neural environment, thus enhancing the experimental internal validity.

[28] However, even public behaviors to which we generally attribute simple response definitions are, indeed, very complicated if analyzed in terms of the number of muscles involved, of the different contribution of the single muscles or in terms of the exact timing of each contribution.

To further fit the needs of this complex neurobehavioral scenario, in which billions of neurons are acting at the same time, the *neural operational definition* of a target behavior needs to include an “acceptance threshold” to direct the observation towards the significant activity and to resolve, even partially, the problem of the simultaneous activity of other brain areas that are not significant to the task being performed, but that in some way intersect, even if in minor amount, the neural patterns relevant to the target behavior.

The same complexity operating at both a quantitative (extremely high number of neurons) and qualitative level (presence of simultaneous activity in non-relevant brain areas) requires a series of operations to be performed on raw neural data with the aim of reducing the presence of confounds (noise-related signal components). A part of these operations concerns the correction of possible movement related issues (motion correction) and the proper treatment of differences in the times of acquisition of data (slice scan time correction), that are usually registered as a series of successively measured 2D slices. Moreover, other kinds of operations can be performed to minimize physiological noise and let stimulus-related activity pass (high-pass filtering). Even the definition of *predictors* of the signal time course, as an analytical description of the relevant factors and of the possible confounds, accounts for the identification of the stimulus-related activity in the enormous complexity of the neural events potentially detectable in the same unit of time, and for a guided, yet to some degree more decisive observation of the desired activity. In the experiment, separate predictors were defined for separate types of stimuli, including cue stimuli which were considered as confound predictors.

4.3 Results and Discussion

“Cooperative working” being an unavoidable feature of neural behaviors, we need to study “patterns” of neural activity, since they are the obliged minimal topography of neural behaviors.

The verbal operants studied in this experiment were clearly distinguishable from each other on the basis of the allocation of neural resources needed to produce them, so that “specific protocols reproducing the controlling variables of each verbal operant in the functional neuroimaging environment produce[d] specific patterns of brain activity” that could be recognized with a simple visual analysis and were “as unique as the classes of contingencies they reflect.” (Pappalardo et al., 2019, p. 26).

The experiment provided a “neural fingerprint” of each verbal operant on the basis of the location and the amount of neural resources used in each cerebral lobe:

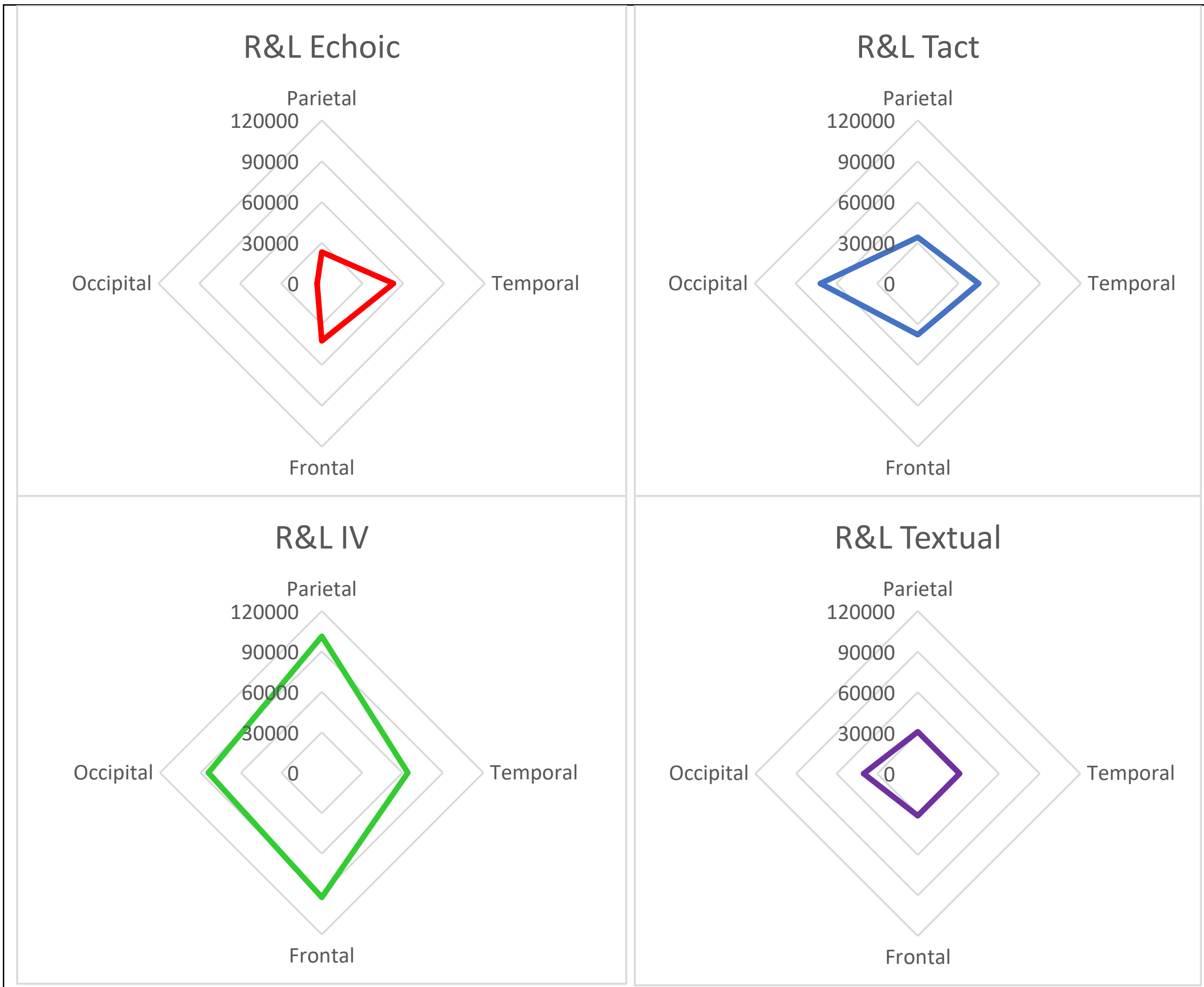
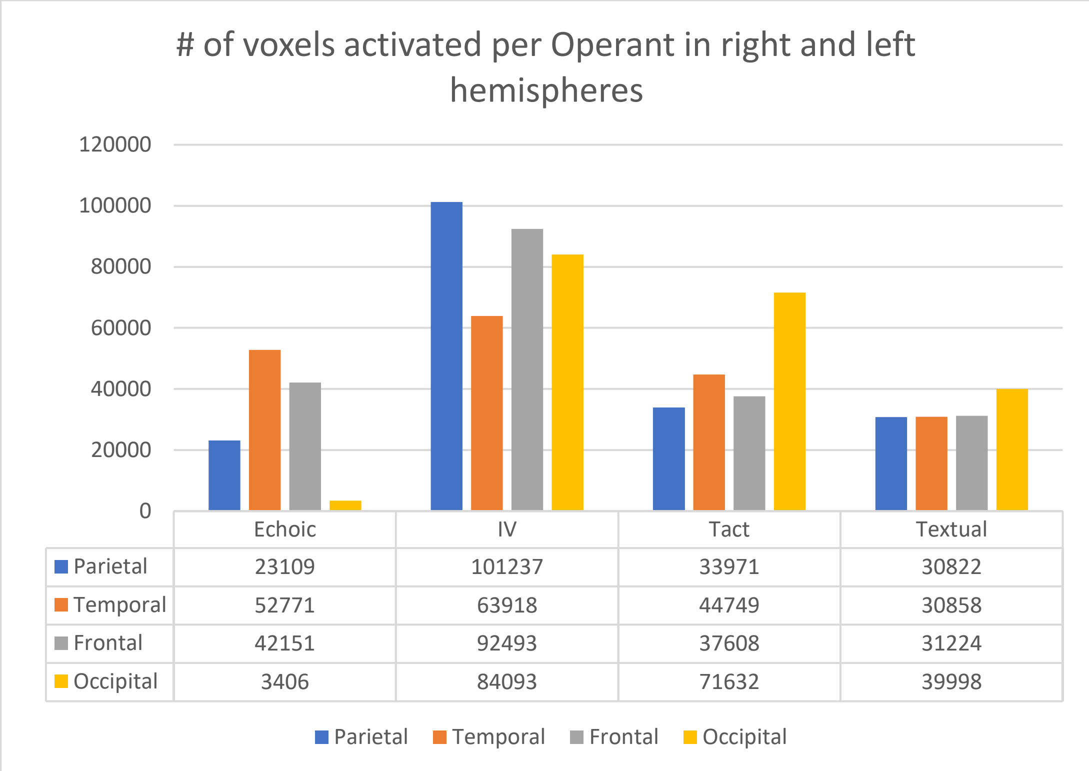


Fig.1 - Synopsis of the neural fingerprints related to verbal operants (lobar distribution of activity patterns). Most of the ecoich related activity is centered in the temporal lobes. The tact and textual operants correlate to a prevalent activity in the occipital lobes. The intraverbal is characterized by a wider distribution of the activity pattern in all brain lobes, with a prevalence in the parietal lobe.

The same analysis can be displayed in a more conventional form with a bar graph and the corresponding table:



	Echoic	IV	Tact	Textual
Parietal	23109	101237	33971	30822
Temporal	52771	63918	44749	30858
Frontal	42151	92493	37608	31224
Occipital	3406	84093	71632	39998

Fig. 2 – Number of voxels activated per verbal operant in right and left hemispheres.

Echoic

The analysis of the activity patterns related to the echoic operant shows a prevailing spatial involvement of the temporal lobes, meaning that the highest amount of neural resources are recruited from the temporal cortex. These results are consistent with Skinner's description of the contingency of the echoic operant, which implicates only auditory stimuli and response products of the same nature[29], and with the involvement of the superior surface of the temporal lobes in the processing of auditory stimuli, as an extensive neuroscientific literature (Formisano et al., 2002; Seifritz et al., 2003) has shown. This same pure auditory nature of the stimuli involved in the echoic contingency also explains well the very low amount of neural resources employed in the occipital lobes, where the neuroscientific literature has clearly demonstrated a prevailing processing of visual stimuli (Sereno et al., 1995).

[29] "the response generates a sound-pattern similar to that of the stimulus" (Skinner, 1957, p.55).

The activity in the frontal lobe is less pronounced than in the temporal lobe, with a huge difference between the word and non-word conditions, as shown in Fig. 3:

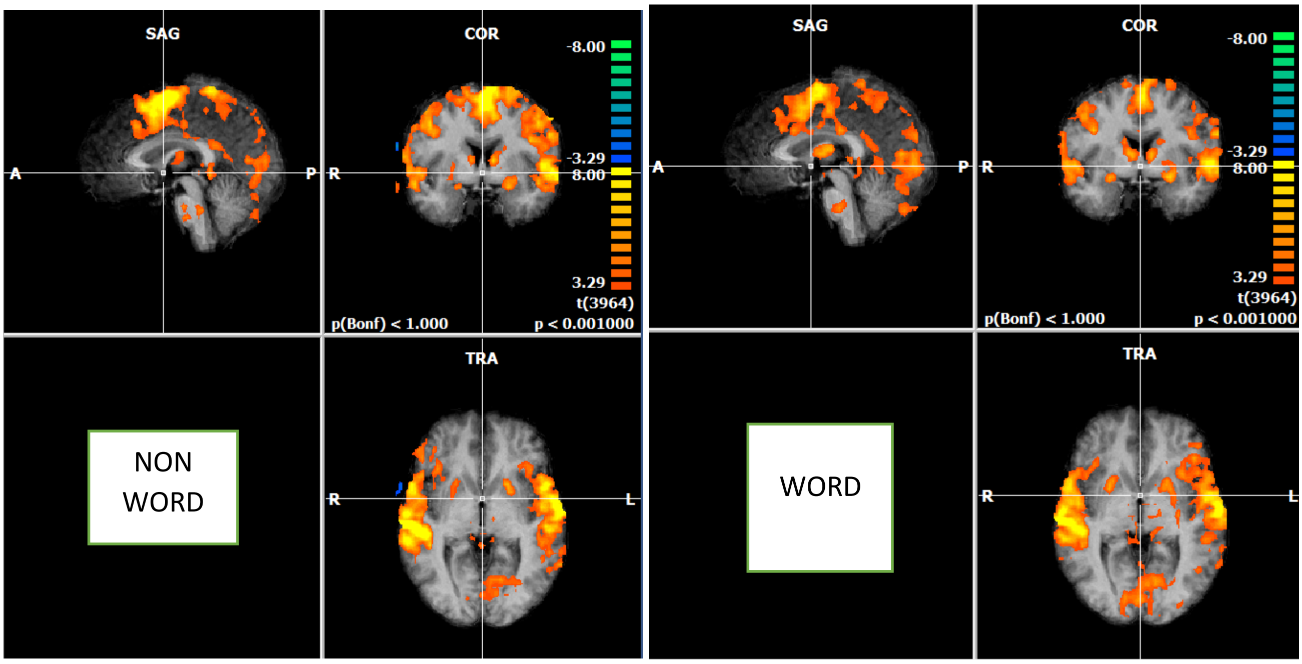


Fig. 3 Difference in activation related to the echoic operant in the word (right) and non-word (left) conditions.

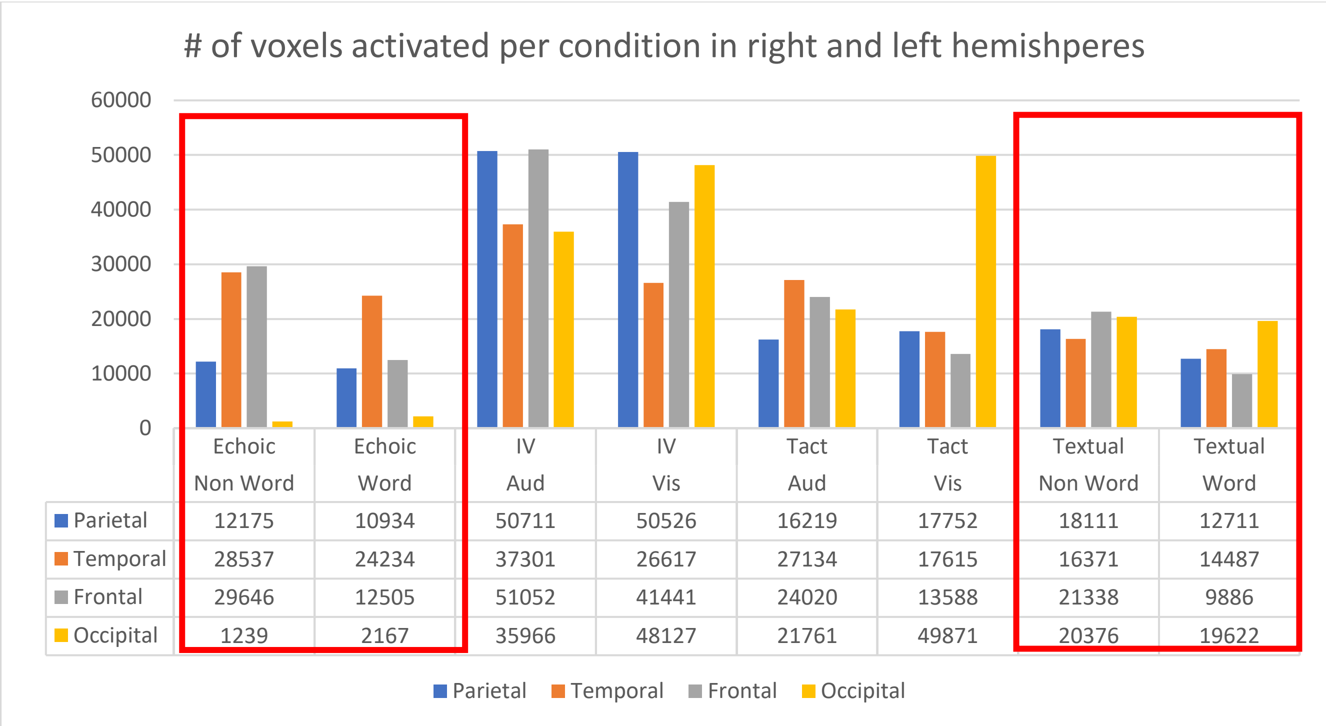
This difference is likely related to the use of "memory" in the emission of echoic responses. In contrast to any task using a visual stimulus, where a substantial part of the stimulation persists during the time needed to emit the response, a task relying only on a pure auditory stimulation needs to let the stimulus persist, which is attainable through "memory" processes. The need for active "memory" processes to support the stimulus persistence increases parallel to the complexity of the vocal/verbal stimulation, reflecting an incremental allocation of neural resources depending on the response effort. The topic of memory has been conceptually discussed in the behavior analytic literature and widely studied by the neurosciences. In the absence of sensory input, to maintain the information in what neuroscience calls "working memory", it is crucial to activate some kind of "stationary process" through the circulation of stimuli back and forth in between specific brain regions and the relevant sensory cortex, involving extensively frontal areas (Eriksson et al, 2015; Mustovic et al., 2003) in the region neuroscience calls the Dorsolateral Prefrontal Cortex (DLPFC). "Keeping the stimulus active" creates, in other words, the neural "configuration" of verbal private mediation strategies that functionally underpin the self-echoic behavior at the neural level. The prevalence of the frontal activity in the non-word condition suggests a greater neural amplitude of the self-echoic behavior in the case of a stimulus (like a non-word) exerting reduced discriminative functions but evoking "purer" echoic responses (less likely to be multiply controlled). A residual evocative power, the absence of a learning history for a "non-word" stimulus notwithstanding, is possible, given the particular characteristics of the echoic repertoire and its faster generalization with respect to the other verbal operants (Skinner, 1957).

What neurosciences define "memory", can be identified as the complex of activities/strategies performed at the neural level and aimed at preserving, along time, the stimulus control over a particular response, coping well with the idea that "memory" is linked to stimulus control as in conceptual frameworks already proposed in the behavioral literature (Palmer, 1991). The main point of this conceptualization consists in the need for that exact stimulus to persist in order to be able to exert stimulus control. The greater involvement of the frontal cortex in tasks where a non-word is present probably reflects a stronger effort of the private mediation links of a hypothetical behavioral chain leading to the public "output" echoic response. In this behavioral chain, intermediate links would need to avoid a progressive decline in stimulus control paralleling the latency for the emission of the public target behavior.

The use of sense and nonsense words as antecedents was designed to reduce in the first place the possibility of emission of private multiply controlled responses (echoic-tacts or echoic-intraverbals). Accordingly, the activation in the occipital cortex shows a substantial prevalence in the "word" condition, suggesting some kind of involvement of private visual mediation in the echoic response to "word" stimuli. Although the difference percentage of parietal activation between the two said conditions is minor, also the parietal activation would appear to suggest that what is being observed is a phenomenon related to the visual manipulation performed by the parietal cortex, as in the visualization of the stimuli in the form of written words or in the expression of some kind of problem solving strategy consisting in trying to "manipulate" the stimulus and generate, once again, a more "powerful" stimulus, as can be one with already established discriminative functions, like a more evocative version of the stimulus itself (i.e, trying to anagram the "non-words" to find a "word").

Textual

The pattern of activation related to the textual behavior appears to be the least differentiated, with a similar amount of neural resources employed in the temporal, frontal and parietal cortexes, and, as it happens for the tact, a more pronounced activation of the occipital lobes with respect to the other lobes (see Fig. 1, bottom right panel). The occipital activation shows no significant difference between the words and non-words, possibly because the visual stimulus remains present across the whole duration of the task for both of them, and consequently it does not need to be "recreated" at the private level in order to maintain or even enhance its evocative power. Since textual and echoic share the presence of a "word" and a "non-word" condition in the experiment, their activity pattern can be compared in the two conditions:



	Echoic Non Word	Echoic Word	IV Aud	IV Vis	Tact Aud	Tact Vis	Textual Non Word	Textual Word
Parietal	12175	10934	50711	50526	16219	17752	18111	12711
Temporal	28537	24234	37301	26617	27134	17615	16371	14487
Frontal	29646	12505	51052	41441	24020	13588	21338	9886
Occipital	1239	2167	35966	48127	21761	49871	20376	19622

Fig. 4 - Total number of voxels activated per condition ("word" condition vs "non-word" condition) in parietal, temporal, frontal and occipital lobes in both brain hemispheres.

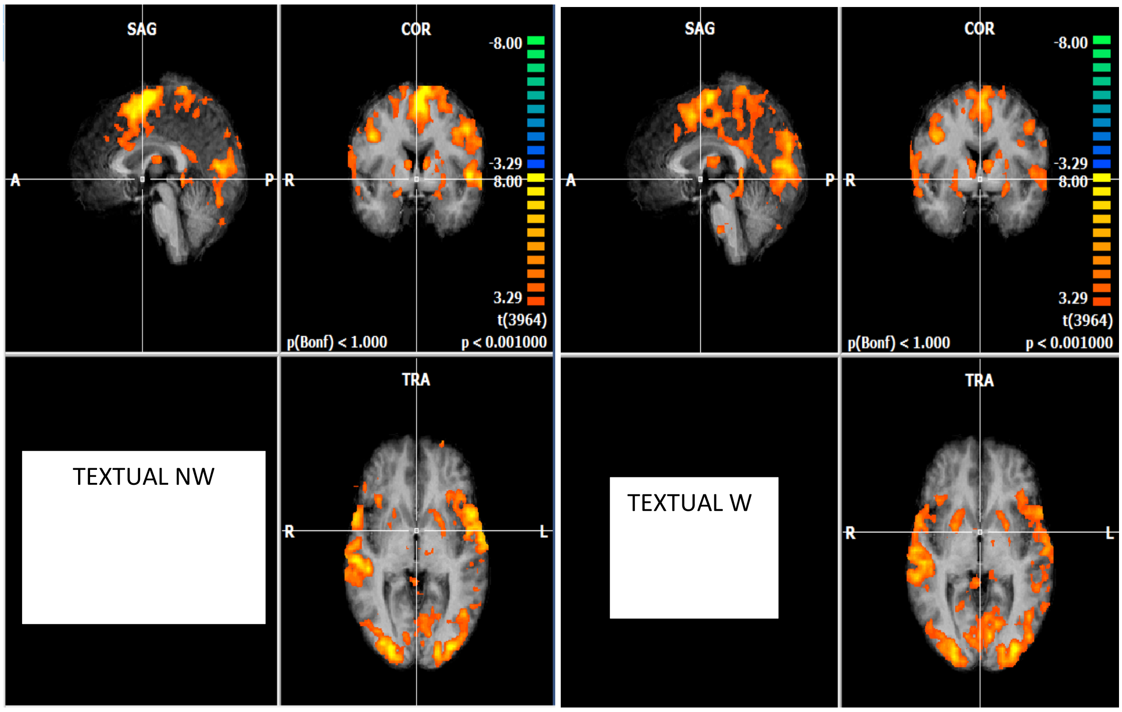
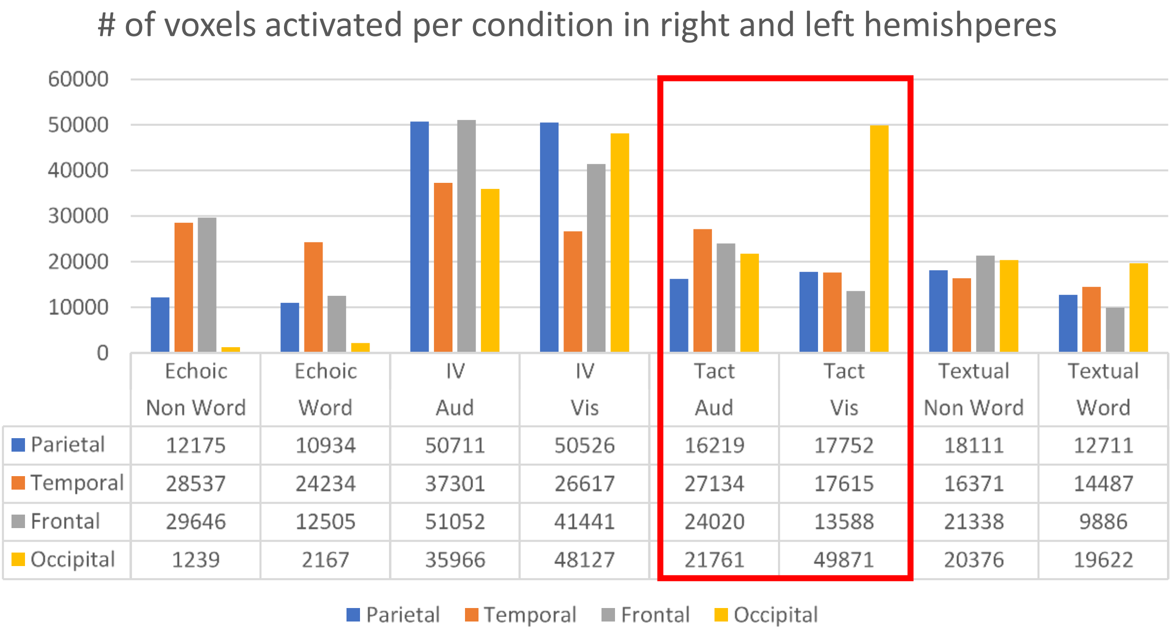


Fig. 5 - Difference in activation related to the textual operant in the word (right) and non-word (left) conditions.

revealing a similar prevalence of the non-word condition in temporal, frontal and parietal regions, where similar "memory" and other possible stimulus manipulation strategies can be active. The reduced amount in the textual of the auditory stimulation (only the response product has an auditory nature), can explain a reduced extension of the temporal activity compared to the echoic, with a prevalence for the "non-words" condition. The differential activation in the word and non-word conditions can find different conceptualizations in the frontal compared to the parietal lobe. Given the presence of "memory related activities" in the frontal lobe, the prevalent activity in the "non-word" condition suggests neural "memory" strategies aimed at avoiding the decay of stimulus control. The differential activation in the parietal lobe suggests, instead, a visual manipulation of the information provided by the stimuli, which has been showed by the neuroscientific literature to have its core in the parietal lobes and in particular in the intraparietal sulci. In the textual operant this phenomenon is accentuated compared to the echoic operant because of the visual nature of the stimuli.

Tact

The "fingerprint" of the tact operant is marked by a more pronounced activity in the occipital lobe, where neurosciences locate the core of vision-related processing. The occipital activation is present in both the conditions comprised in the experiment (auditory tact and visual tact), even if more prominent in the visual one. The occipital activity in the visual tact can be explained by the perceptual public tact contingency, but the presence of occipital activation also in the auditory condition suggests that the emitted public response is mediated by visual private stimuli also in the absence of public visual stimulation:



	Echoic Non Word	Echoic Word	IV Aud	IV Vis	Tact Aud	Tact Vis	Textual Non Word	Textual Word
Parietal	12175	10934	50711	50526	16219	17752	18111	12711
Temporal	28537	24234	37301	26617	27134	17615	16371	14487
Frontal	29646	12505	51052	41441	24020	13588	21338	9886
Occipital	1239	2167	35966	48127	21761	49871	20376	19622

Fig. 6 - Total number of voxels activated per condition ("auditory" condition_ vs "visual" condition) in parietal, temporal, frontal and occipital lobes in both brain hemispheres for the tact operant.

Conversely, the temporal lobe activity is more pronounced in the auditory condition of the experiment, probably due to the combined nature of the antecedent non-verbal stimulus and the auditory instruction "What is it?", whereas in the visual condition the less pronounced neural activity in the temporal cortex is probably due to the presence of the auditory instruction alone.

The “fingerprint” of the tact also includes parietal activation:

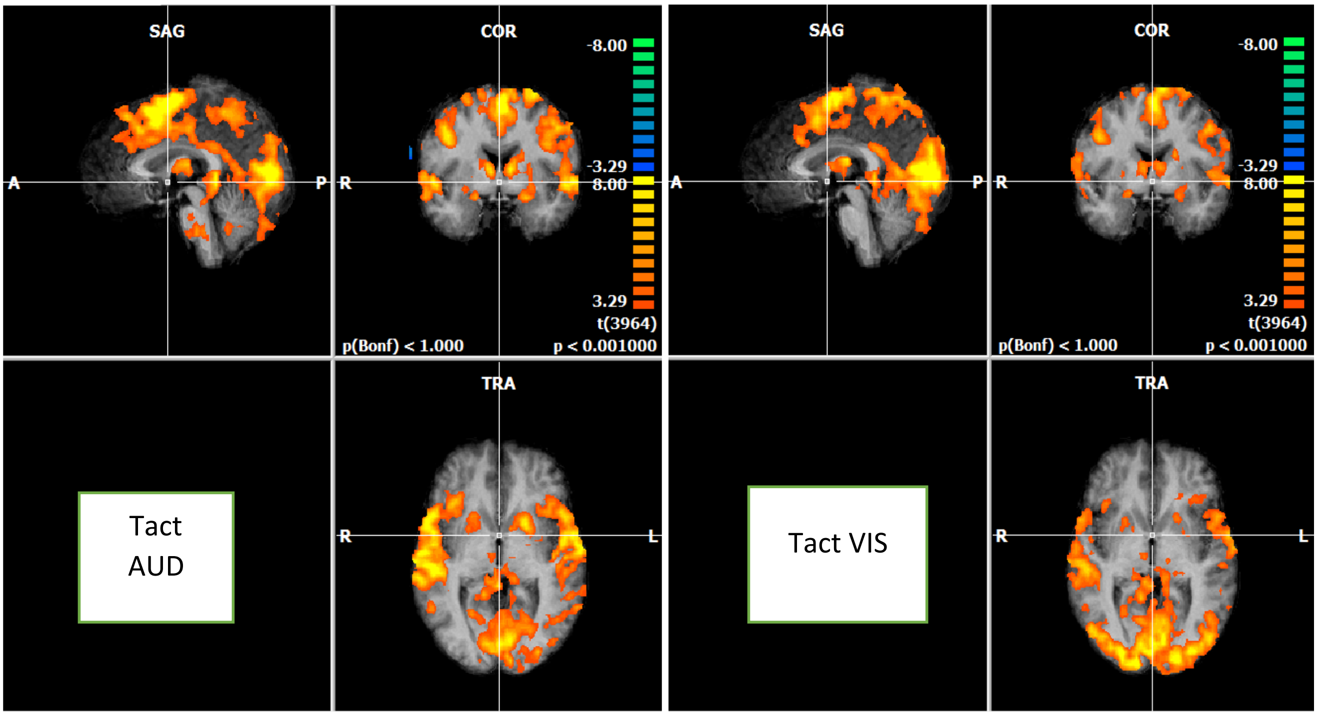


Fig. 7 – Parietal activation in the intraparietal sulci in the two conditions of the tact operant.

Interestingly, in addition to linking to the parietal cortex the neural processing related to the construction of visual images (Formisano et al., 2002), neurosciences locate in the parietal lobe a specific convergence of the pathways of visual perception and imagination (Trojano et al., 2000; Sack et al., 2002). The parietal cortex is also involved in execution of tasks in which participants are asked to name the category of seen objects, and thus considered involved in “semantic processing” (Devereux et al., 2013). B.F. Skinner addresses “semantic theory” in the book *Verbal Behavior* (“The problem of reference”) in the particular case of the tact. He notes that a linear relation is often supposed to exist between an uttered response and, let’s say, a particular object, but that, in reality, “there is always an element of abstraction” (Skinner, 1957, p. 117). The “semantic process” or, as Skinner writes, the “idea” of something is then possibly operationally defined by a private mediation operated by the parietal cortex checking if a stimulus belongs to a particular class of stimuli. As much as this phenomenon can share its dynamics with stimulus generalization processes, the presence of parietal activity in the tact “neural fingerprint” is intriguing, because it suggests that, in the presence of non-verbal stimulation and even of a particular history of reinforcement, the public tact possibly requires some contribution by a private imaginative mediation, and potentially reflects that perception and imagination are linked to each other. In this scenario, perception and imagination work together in a way that involves possible private category tact responses performed at the level of the parietal cortex in the very moment in which a simple tact is emitted. The parietal activation found in the tact is common to the two conditions it comprised in the experiment (see Fig. 7), suggesting a shared phenomenon independent of the antecedent stimulus nature.

Intraverbal

The neural activity related to the intraverbal operant is definitely marked by the richest pattern of distribution, which parallels the complex nature of this operant. Sautter & LeBlanc (2006) noted that "this operant includes perhaps the most diverse group of responding and accounts for reading comprehension, conversation, and question answering and events that are traditionally conceptualized as thought or memory" (p. 41), and encouraged to conduct more research on the topic. The attention dedicated to the intraverbal by the behavior-analytic community has in fact increased lately (Aguirre et al., 2016), and it has also involved further investigation on its definition (Palmer, 2016).
The intraverbal word association task executed in our experiment comprised auditory or written (visual) stimuli, allowing a comparison between the spatial distribution of neural resources across these two different stimulus conditions. Both the conditions comprised though an auditory instruction to associate that can be responsible for the temporal lobe activation in both of them, together with the auditory product of the response. The wider activation of the temporal cortex in the auditory condition suggests the involvement of private self-echoic behavior in the absence of a steady representation of the antecedent stimulus. This is in keeping with Skinner's analysis of the "word association" activity. In *Verbal Behavior* (1957) Skinner talks about the "word association" experiment, conceptualizing that echoic control is probably involved in the production of even a single word association and acknowledging the possibility of the emission of an echoic behavior beginning from the very first moment, unless the participant is instructed not to do so:

"In the standard "word association" experiment, a stimulus word is presented, and the subject is asked to report the first word he finds himself saying in response to it. It is necessary to instruct the subject not to repeat the stimulus word; even so, a fragmentary echoic behavior appears in what are called "clang associations" – responses which are alliterative or rhyming or otherwise similar to the stimulus word." (Skinner, 1957, p. 56).

In a broader perspective aimed at comparing both tact and intraverbal tasks which contained visual and auditory stimulation in the experiment, data show that the activity in the temporal and frontal cortices is consistently stronger in the auditory condition, probably aimed at increasing the persistence of the antecedent stimuli. Temporal and frontal cortices are so possibly active in reproducing over time the stimulation, preserving the stimulus control over the response from decay.

The prominent activation in the intraverbal pattern is parietal. Neurosciences have linked parietal activity to tasks in which private visualization activity is involved (Knauff et al., 2000), and in particular fMRI experiments have shown that a specific region in the parietal cortex, the left Intraparietal Sulcus, is actively involved in the generation of mental images (Formisano et al., 2002). The extended parietal activation found in the intraverbal, the same that marks its "fingerprint" with respect to the other operants, suggests then a significant involvement of imagination in intraverbal tasks.

We found the same activation of the parietal cortex in tact and intraverbal and this finding is in line with the specificity of parietal activation in imagination tasks and, as pointed out for the tact operant, the convergence of the pathways of imagination and visual perception in this same cortex. Neurosciences suggest that a common neural basis exists for the analysis of visual neural activity in both perception and imagination. The parietal activity is similar in the visual and auditory conditions, suggesting a possible stable involvement of imagination in the intraverbal behavior regardless of the nature of the antecedent verbal stimulus. The results also suggest that the possible imagination activity mediating the emission of the intraverbal public response is accompanied by occipital activation, which is typically related to visual perceptual activity. The visual condition presents a greater occipital activation, possibly because of the nature of the antecedent stimulus, but occipital activity is still present in the auditory condition, suggesting a common involvement of visual perceptual activity in the intraverbal, the distribution of neural resources in the occipital lobes being consistent with the one found in the tact.

Neural underpinnings of the functional independence and interdependence of the verbal operants

The identification of different neural patterns for each operant uniquely corresponding to their overt occurrence can be itself a demonstration that they are to some degree functionally independent from each other. But, once observed and specifically defined, the patterns of neural activity related to the verbal operants could be further studied "contrastively" and "jointly", so to outline the neural underpinnings not only for their functional independence, but also, as Skinner (1957) pointed out, their interdependence, in other words the multiple control of verbal behavior. Since they are commonly used in neuroscientific experiments, "contrast" and "conjunction" analyses were performed, but this time with the aim of highlighting the neural specificities pertaining to each pattern, as neural basis for the functional independence, and of identifying their commonalities (i.e. the brain areas in which the neural patterns overlap), which were considered a neural demonstration of multiple control. Conceptually, a contrast analysis has to involve two components. With respect to the specific analyses performed, a component was represented by the operant of interest, and the other one was represented by the echoic, this operant being the one employing the least amount of neural resources and having more of the features, even at the neural level, of an "atomic repertoire" (Palmer, 2012). As Palmer (2012) defines it, an *atomic repertoire* is "a set of fine-grained units of behavior […] Like letters on a page that can be arranged to display a great variety of expressions, atomic responses can be arranged to meet a great variety of contingencies" (p. 61). As such a repertoire, echoic activity could then be consistently "subtracted" from the neural pattern that was being studied in that particular moment to show the specificity of brain activation of the corresponding verbal operant.

The contrast analyses performed have shown the neural specificities of the intraverbal, i.e. the brain areas that were differentially activated during its public emission, for example the huge activity in the parietal cortex:

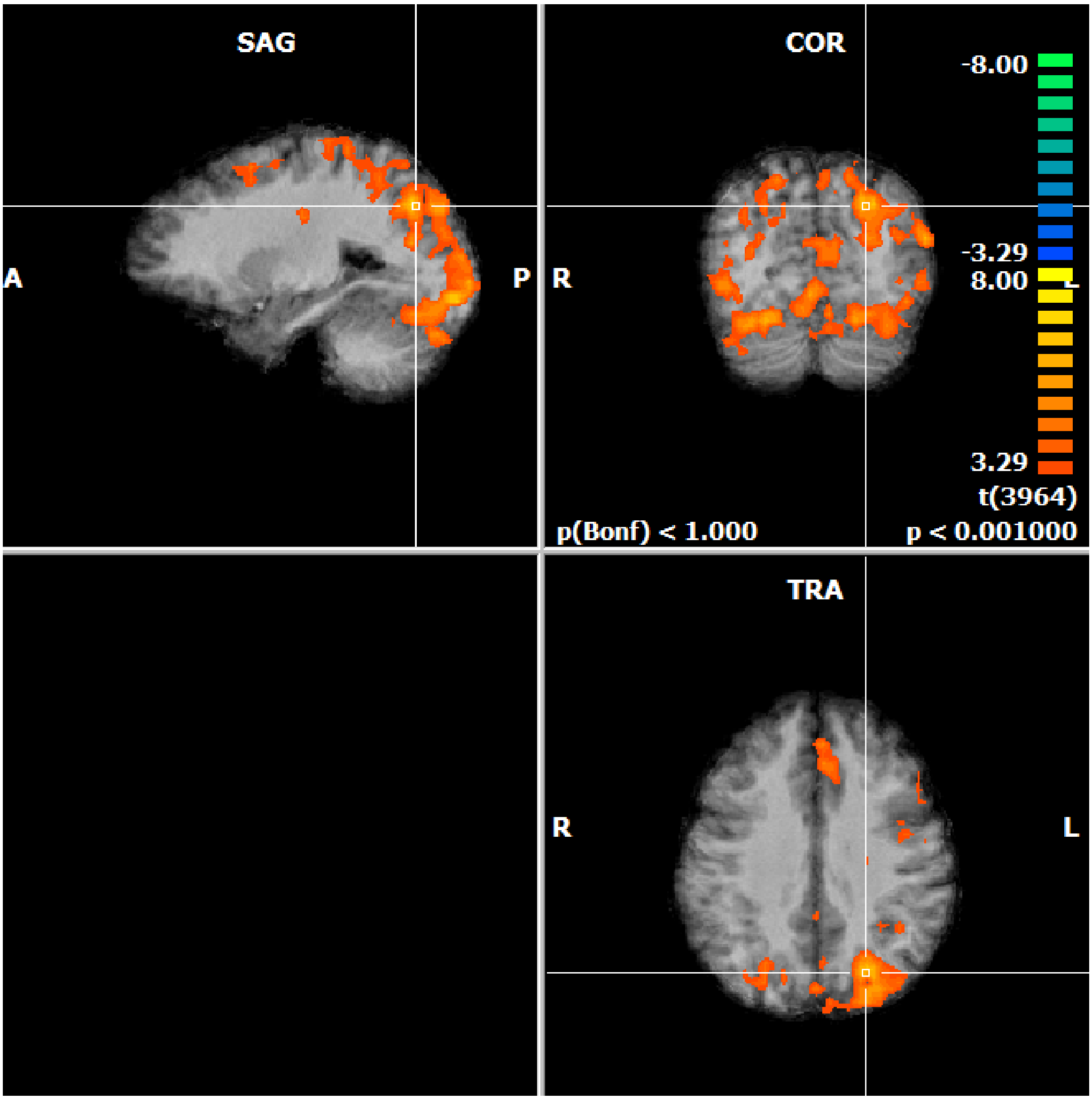


Fig. 8 – Specific brain activation in the parietal cortex for the intraverbal.

or the activity in the occipital cortex:

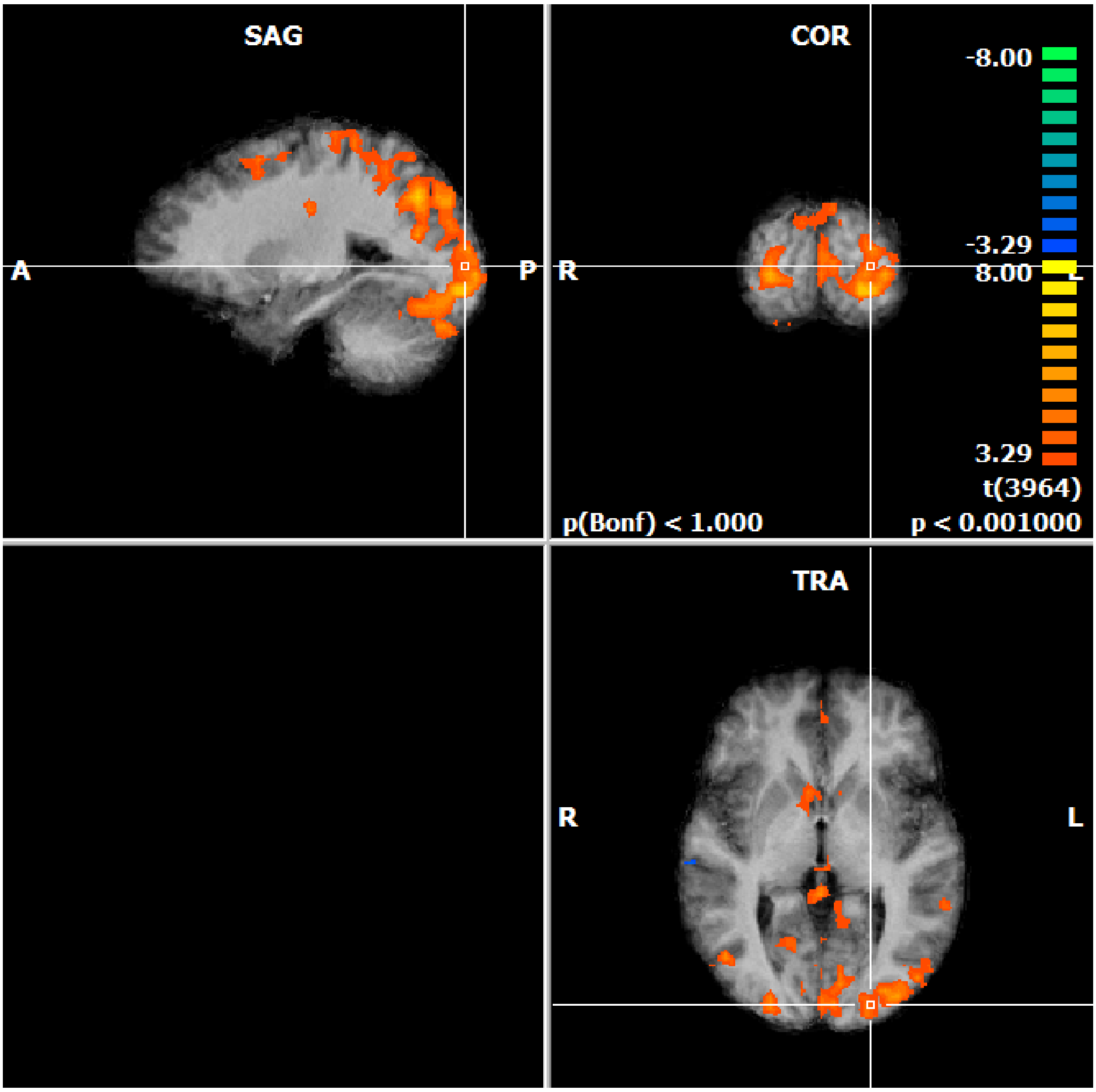


Fig. 9 – Specific brain activation in the occipital cortex for the intraverbal.

Also for the tact operant, the contrast has shown the specificity of its pattern, which certainly reside in the prominent occipital activation:

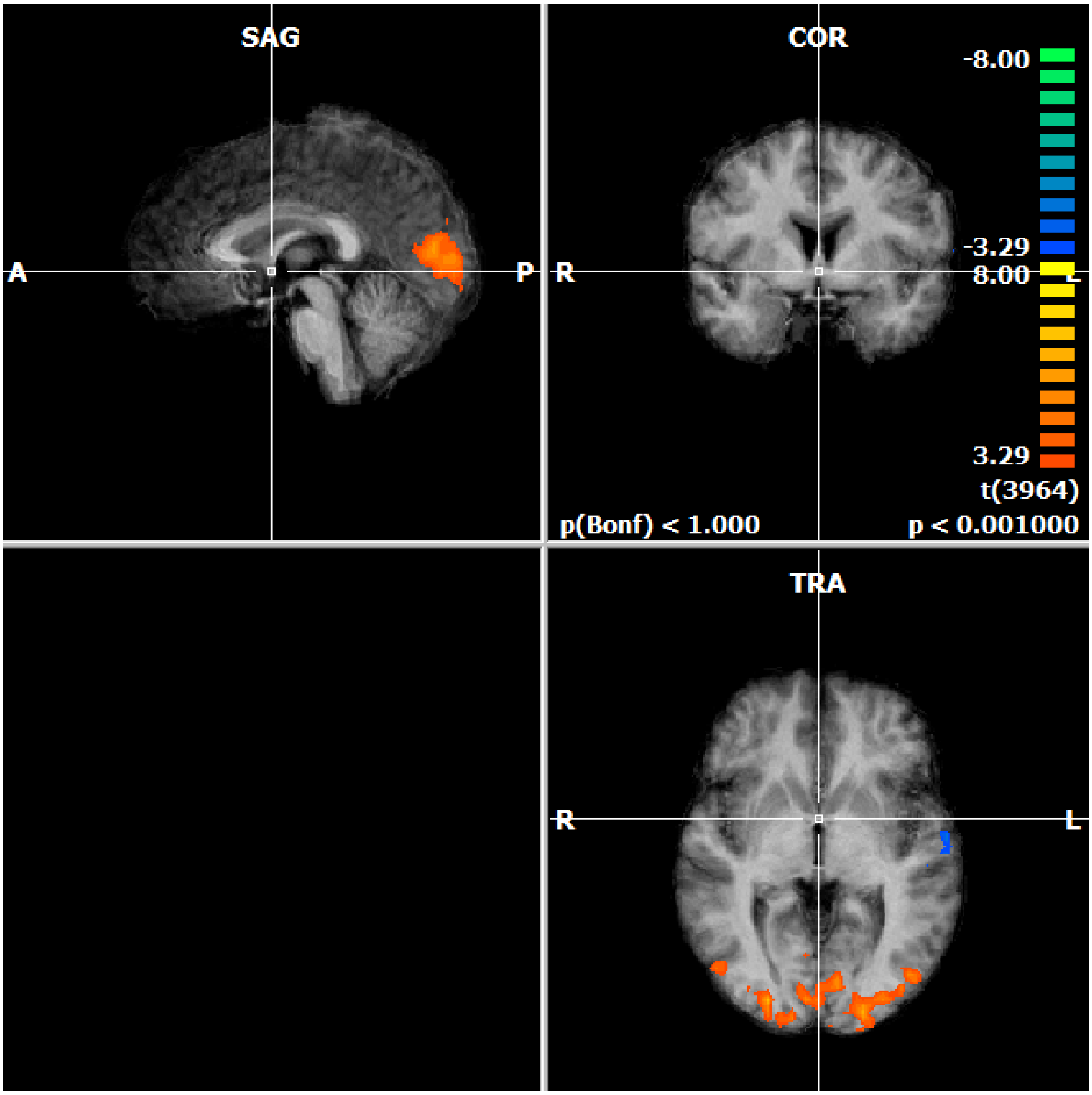


Fig.10 – Specific brain activation in the occipital cortex for the tact.

Special attention was dedicated to the study of the neural loci in which the pathways of tact and intraverbal overlapped. As shown in the following figure:

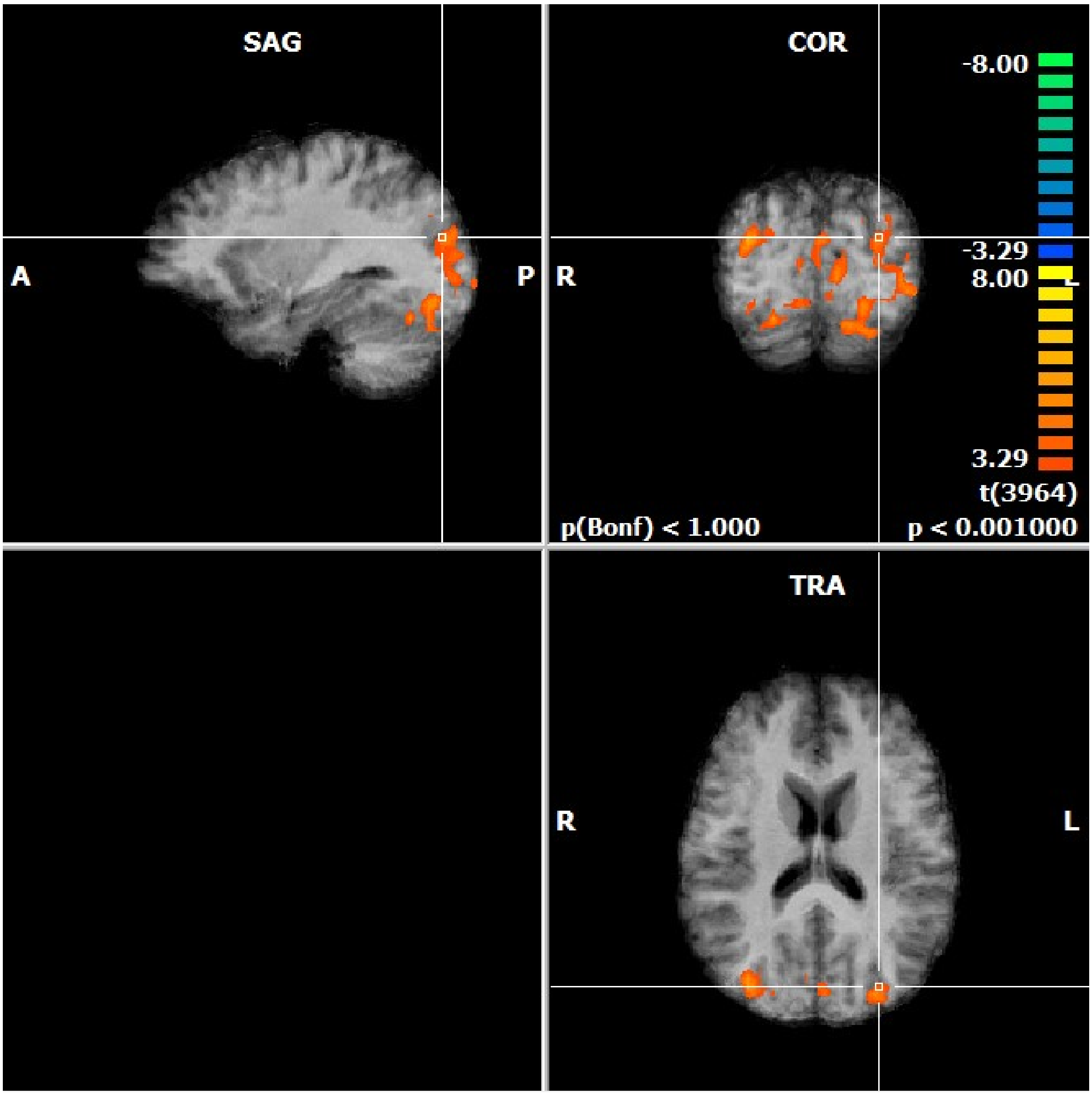


Fig. 11 – Brain activation observed in the conjunction contrast (Tact vs Echoic) and (Intraverbal vs Echoic) performed on the activity patterns of tact and intraverbal.

the specific region of overlapping is the Intraparietal Sulcus (IPS) which, as previously discussed, has been linked by the neuroscientific literature to imagery activity and to visuospatial mental imagery - i.e. the generation and manipulation of visual images (Knauff et al., 2000; Formisano et al., 2002; Trojano et al., 2000). By providing an observation of the commonalities existing in the neural patterns of the tact and the intraverbal, the results of this more sophisticated analysis of neural verbal behavior seem to provide evidence about the critical role played by visual imagination in both the tact and the intraverbal operants (Pappalardo et al., 2019), like Skinner had anticipated when discussing about imagination in terms of emission of perceptual behavior at a private level, as in “seeing in the absence of the thing seen” (Skinner, 1974, p. 91).

SECTION III: APPLICATIONS TO LANGUAGE TEACHING STRATEGIES

CHAPTER 5

STUDY 3: IMPROVING THE INTRAVERBAL REPERTOIRE THROUGH A *TACT TRAINING* PROCEDURE

5.1 Introduction

The purpose of study 3 has been to investigate the possibility of improving public verbal repertoire through *specific* teaching strategies which were conceptually underpinned by the *analysis of neural behavior* and by the definition of the patterns of activity related to the verbal operants.
In particular, the intraverbal behavior in the form of word associations was studied.

In the last 15 years, the behavior analytic literature has shown increasing interest in the intraverbal relation. Aguirre et al. (2016) point out that "some authors have evaluated a correlation between age and correct intraverbal responding with typically developing children and children with autism, which may be useful in the development and assessment of simple and complex intraverbal responding (Sundberg & Sundberg, 2011). The term verbal conditional discrimination has been introduced for when a verbal stimulus alters the evocative effect of another verbal stimulus in the same antecedent event and when verbal behavior is under sources of multiple control (Michael, Palmer, & Sundberg, 2011; Sundberg & Sundberg, 2011). Additionally, Axe (2008) has since provided a further evaluation of complex intraverbal responding that are under divergent and convergent control" (p. 140). Moreover, behavior analytic literature has explored the effects on intraverbal responses of stimulus control transfer procedures based on tact prompting and instruction (Ingvarsson & Hollobaugh, 2011; Grannan & Rehfeldt, 2012; Feng et al., 2017) and the efficiency of prompting tactics were also evaluated (Goldsmith et al., 2007; Ingvarsson, 2011a; Ingvarsson, 2011b; Kodak et al., 2012). An efficacy of both picture and echoic prompts was reported, with the picture prompts resulting in some cases in fewer trials to skill acquisition criterion (Ingvarsson & Hollobaugh, 2011). Multiple-tact training has also been investigated for the emergence of visual categorization (Ribeiro & Miguel, 2020).

Since it is an everyday life problem solving strategy, for instance when "recalling past events, giving geographical directions, and solving math problems" (Axe et al., 2018), visual imagining was used as an independent variable for increasing intraverbals. Kisamore et al. (2011)[30] and Aguirre & Rehfeldt (2015) investigated the possibility of teaching visual imagination and showed that prompting the use of an imaginative strategy increased intraverbal responding to intraverbal categorization questions (Kisamore et al., 2011) or that it increased spelling (Aguirre & Rehfeldt, 2015). Auditory imagining instruction procedures have also been investigated (see Mellor et al., 2015).

Our study evaluated a *tact training* procedure as an independent variable to increase intraverbal responding in typically developing adults.

5.2 Methods, Data Collection and Experimental Design

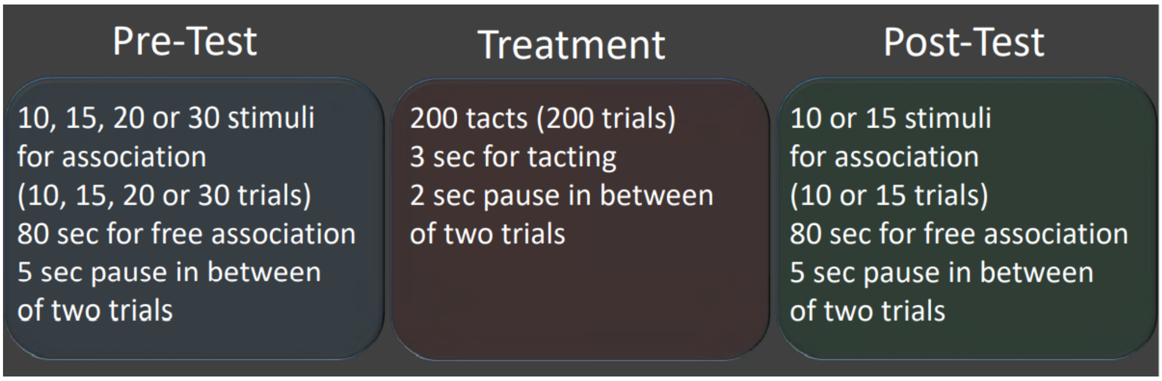
A number of 19 typically developing Italian mother-tongue adults divided in four groups participated in the study. All sessions were conducted in a quiet area of the laboratory, where participants were asked to sit in front of a laptop, and any possible source of distraction was eliminated. In fact, most of the items present in the room were removed from the participants' sight, not only to minimize the sources of distraction, but also the possible "prompting" effect of the surrounding environment. Two experimenters seated behind the participants and registered their responses in the same room in which the experiments were carried out. Sessions lasted approximately 1 hour and were conducted just once for each participant. After each phase, participants were free to take a few minutes break if they felt they needed it.
The materials used consisted in a laptop containing specific experimental scenarios which had been designed by the experimenters utilizing a stimulus delivery software (Presentation®).

The experimental protocol consisted in three phases: a word association *pre-test*, a *tact training* and a word association *post-test*.
During the *pre-test*, that lasted approximately 20 minutes, participants were instructed to listen to single words auditory stimuli provided by the stimulus delivery software, to try to generate private visual images from them and, on that basis, to orally produce, one by one,

[30] Extending Sautter et al. (2011).

single word[31] associations (e.g., answering “moon”, “sky”, “shooting star” after the word “night”). The total number of trials in the *pre-test* phase varied from 10 to 30, with a maximum of 15 stimuli per single *pre-test* run. During each trial, the participants could produce their responses in a 80 second interval, and an interval of 5 seconds pause in between two successive trials was present. The auditory stimulus “Stop” signaled the end of a trial and the stimulus “Associate” followed by the specific word marked the beginning of a new trial.

During the *tact training*, which lasted approximately 15 minutes, a series of pictures of common items and from the computer screen were showed to the participants, who were required to label them, so emitting a series of tact responses. In this phase, no particular requirement to produce single word utterances was present. Each participant was asked to tact 200 pictures, and the total duration of each tact trial was 5 seconds (3 seconds duration per picture presented and 2 seconds pause in between two successive trials).
The *post-test* phase was designed just as the *pre-test* phase, but it was conducted after the *tact training*.
The following figure provides a visual representation of the experimental protocol:



From: Di Salle, F. Ianniello, M., Pappalardo, E., *Modifying the Intraverbal Response through the “Crossword Effect” and Neuromodulation Techniques,* National Autism Conference 2020, session # 34.

The words used in all the experimental phases were selected so that they had no semantic similarities with each other. The semantic relatedness of words was calculated on the basis of a corpus-based distributional semantic model (WEISS, Word-embeddings Italian

[31] In a limited number of cases, the participants produced compound (two-word) responses, but this variation was not found to be jeopardizing the experimental procedural integrity.

semantic spaces; Marelli, 2017). This tool provides a numerical value - comprised between 0 and 1- for each word and corresponding to the degree of association existing among the stimuli. For the stimuli selected for the *pre-test* and the *post-test* phases the mean frequency (the frequency of a word's occurrence in a language) was also calculated utilizing an Italian corpus containing about 4 millions of occurrences (CoLFIS, Bertinetto et al., 2005). Since the task to be performed had an imaginative nature, we distributed the stimuli of the *pre-test* and the *post-test* phases also according to their *imageability*, with the aim of expressing in a numerical value the extent to which an auditory stimulus evokes a mental image. The values of word imageability derived by subjective ratings on a 1 to 5 point scale and were provided by thirty people who did not take part into the experiment. Using the same protocol, after the experiment, values of word imageability for the single participants were collected too.

The two hundred pictures comprised in the *tact training* phase were also selected so that there was the least degree of semantic relation with the *pre-test* and *post-test* stimuli.

The primary dependent variable was the number of intraverbal responses produced.

The experimental design used is a nonconcurrent multiple baseline across groups of subjects. Widely used in behavior analysis, the multiple baseline design is an experimental design in which the measurement of the target behavior in the baseline condition is followed by the application of the independent variable to one of the subjects while baseline conditions remain in effect for the other subjects. The target behavior and the setting remain the same for all subjects. In a multiple baseline design the independent variable is applied in sequential fashion and the demonstration of experimental control consists in behavior showing similar changes *when and only when* the independent variable is introduced (Cooper, Heron, & Heward, 2020). In its *nonconcurrent* variation, when concurrent measures are not possible, for example because of difficulties to simultaneously attend to the participants, this experimental design consists in a series of baseline-intervention sequences conducted across subjects at different points in time, but still keeping the basic feature of having different length baseline phases (Cooper, Heron, & Heward, 2020)[32].

[32] Cooper, Heron, & Heward (2020) note that although entailing prediction and replication, the nonconcurrent multiple baseline is intrinsically weaker than other multiple baseline design variations (p. 235).

5.3 Results and Discussion

The results of the experiment show an increase in the number of intraverbal word associations produced by the 4 groups of participants following the *tact training*:

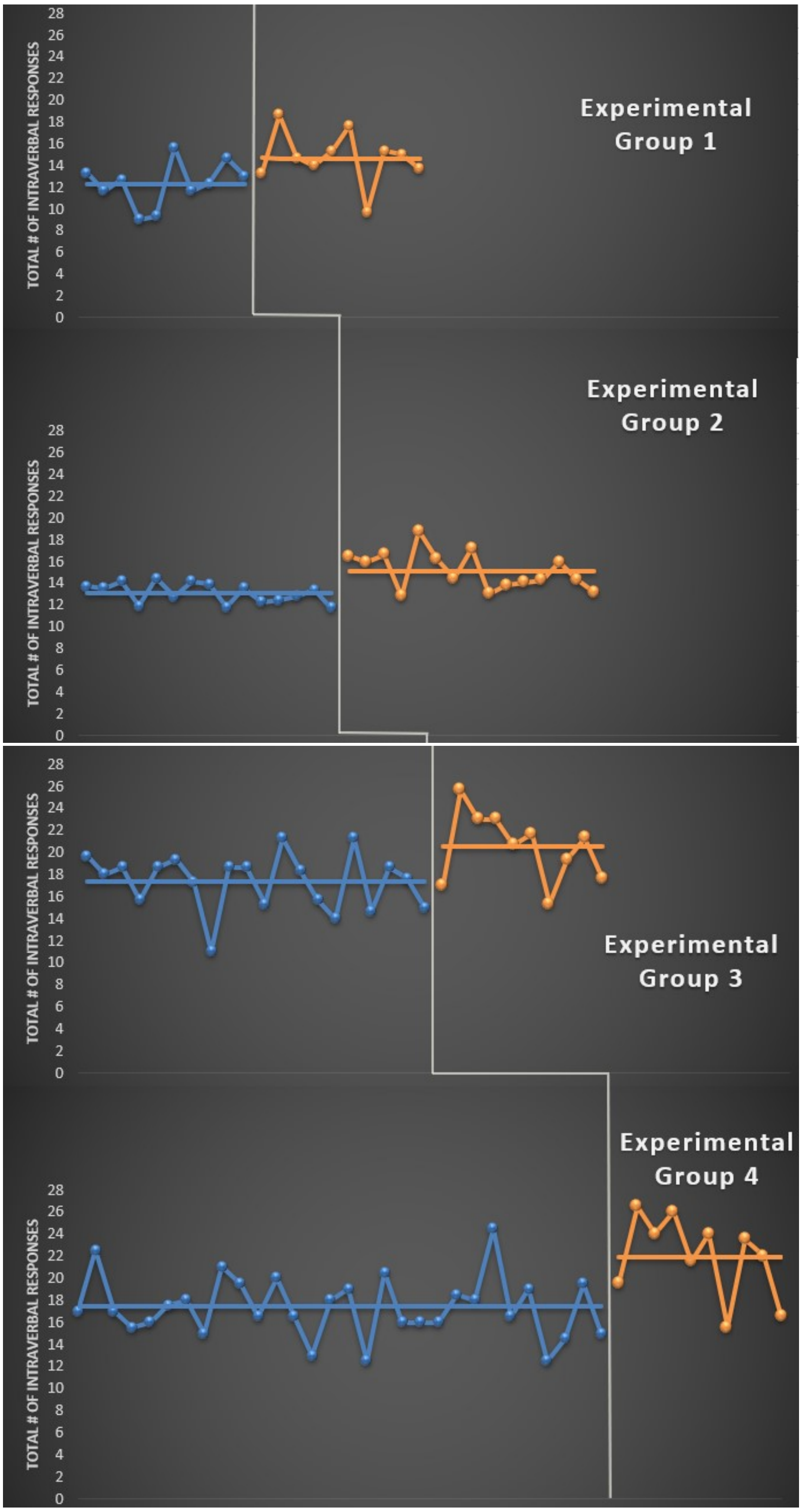


Fig. 1 – Number of intraverbal responses in the *pre-test* and *post-test* phases depicted for each group of participants. The experimental group 1 was composed by 3 participants; the experimental group

2 was composed by 11 participants; the experimental group 3 was composed by 3 participants; the experimental group 4 was composed by 2 participants. The graph shows an increase in the mean production (level) of intraverbal word associations after the *tact training*.

Our *tact training* procedure was designed to be different from the usual tact prompting implemented to teach the intraverbal in the conceptual framework of stimulus control transfer procedures. By involving stimuli which were completely unrelated with the target response topographies, it was conceptually more of a *behavioral momentum* related strategy, that is aimed *specifically* at momentarily increasing the ability of responding and possibly reflecting an enhanced neural excitability in the private part of the behavior. The experiment was aimed at providing a first evidence of the possibility to derive teaching strategies from what we know about neural behavior associated to the verbal operants, by designing an intervention that could provide *independent training* of the tact and intraverbal overlapping area, as in "repairing a weak link" of a possible private and public behavioral chain, to then return to teach the entire chain when the weak link has been substantially and effectively trained.

As a further development of the experiment, it is certainly noteworthy to point out the potential value of a detailed and analytical future discussion on the degree to which the possible use of different imaginative (or non-imaginative) strategies by the participants may have impacted the improved results they achieved in the *post-test*.

CONCLUSIONS

As a conclusion of the present work, the potential application-related implications of the single experiments and future research perspectives will be presented.
The results of the experiments carried out and presented throughout this thesis provide several points for discussion, not only for future research, but mainly because they lay the basis for the inclusion of the analysis of neural behavior in the conceptualization and possibly the implementation of teaching strategies addressed to the establishment and/or the strengthening of overt repertoires, and particularly overt verbal response classes.

Study 1 has explored the possibility of providing a quantitative measure of neural behavior. Without this foundation stone, an empirical analysis of neural behavior would hardly be possible. The value of such an analysis can be remarkable, and its use can be enlightening to the purpose of including in the analysis of overt behavior an acknowledgment of the private neural links constituting part of the complex series of responses linked to each other and leading to a final overt outcome.

The results of Study 3, showing the efficacy of a *tact training* to improve intraverbal performance, open also to a wider application of strategies conceptually equivalent to the *tact training*. By not being related to any particular prompting strategy, but by being based on a potentially momentary effect of synaptic stimulation and a momentary increase of functional connectivity in the overlapping area(s) between two neural patterns, a similar strategy could be implemented with the aim of *specifically* training the "crossword" area between two interrelated neural patterns.

The possibility of implementing such a training wouldn't even exist if there wasn't an empirical strategy to study the functional independence, but also the overlapping of the neural patterns of activity subserving public responses. That is what Study 2 was aimed at in the particular instance of verbal behavior. In Study 2, the specific patterns of neural activity subserving the different classes of verbal responses (verbal operants) were identified and described in their unique features (functional independence) with respect to each other, but also in the neural loci of activity commonalities, which underpins the multiple control of verbal behavior at the neural level and allows to single out the areas that could be the object of a *specific training* impacting the functioning of the overlapping patterns.

Future research should examine the potential role of neuromodulation techniques in establishing new complex verbal repertoires or in strengthening already existing ones. That is, the possibility of using an advanced and innovative set of neuroscientific techniques in a behavior-analytic frame of reference to *directly* modify brain functioning, i.e. as a *teaching strategy* for multiple verbal response classes whose private emission is hosted by brain areas representing a neural locus of intersection between different activity patterns.

Although the disadvantages related to its availability and portability (Tursic, 2020; Linden, 2014) should be considered, fMRI-based neurofeedback provides a better spatial resolution with respect to the other applications of neurofeedback (EEG, MEG) and it can reach deep subcortical structures. While it has been linked to the possibility of deeply investigating neural correlates of mental disorders, fMRI neurofeedback reveals itself also applicable to the study of the private (neural) portion of complex repertoires, namely verbal repertoires, in a possible conceptualization of complex neural behavioral chains linking different brain areas activities to each other and ultimately constituting the neural activity network related to a specific public response class.
The principle on which neurofeedback is based is indeed a learning one: in fact, it consists in a training. More specifically, and in its simple form, in fMRI neurofeedback the feedback is based on the real time analysis of the BOLD (Blood Oxygenation Level-Dependent) signal related to a particular brain area or region of interest (ROI) while the subject is engaging in a particular task, with the possibility of benefitting of the spatial resolution given by fMRI.

A systematic review of real time fMRI-based neurofeedback studies (Tursic et al., 2020) has shown a steady increase of research publications on the topic in the last 10 years. The authors note that fMRI neurofeedback promising results have the potential to influence future treatment alternatives. To date, interest has been shown in the application of fMRI-based neurofeedback for therapeutical purposes (Linden, 2014), for example for the treatment of depression. In a 2014 study, Linden et al. implemented fMRI-based neurofeedback training sessions for patients with major depression, who so learned to self-regulate (upregulate) the activity of a previously identified brain area and resulted in exhibiting a reduced array of depression symptoms after training (Linden et al, 2014). The targeted area was identified before the neurofeedback training, in a localizer session aimed at identifying the ROI involved when the participants thought of positive visual stimuli.

As Russo et al. (2021) note, the learning outcomes related to the improved performance with neurofeedback have been associated with changes in covert and overt behavior not only in the treatment of neuropsychiatric disorders but also in several other domains, ranging from motor function to emotion regulation. These authors have introduced a new neurofeedback method providing the participants with a real-time *content specific feedback*[33] on their brain activity, which guided them to engage in directing, in the absence of any particular suggested strategy, their neural behavior towards a determined correct criterion or in maintaining a particular neural activity. *Content specific neurofeedback* allows the subject to actually see where their brain activity related to a particular designated stimulus is located with respect to other different mental states. It is a new method with respect to the traditional thermometer display -which simply depicts the level of neural activity- because it allows the subject to direct their brain activity based on a more analytical 2D visualization space representing distributed patterns of brain activity within the selected ROI. The current mental state of the subject "is displayed as a movable point on a plane" (Russo et al., 2021, p. 9) which they are required to advance towards the designated target. The increased difficulty in modulating the activity of brain areas, the increased articulation of feedback control, represent a major factor that can significantly modify the impact of neurofeedback on the whole brain functioning.
The possible applications of fMRI neurofeedback techniques to teach new skills at the private and public level is a further demonstration of the fact that the analysis of neural behavior does not have to replace or conflict with the study of overt behavior. It would be, once again, the equivalent of fulfilling B.F. Skinner's expectations about "filling the gaps" existing between them, and to do it even more completely (Pappalardo et al., 2019).

[33] The traditional neurofeedback designs show neural activation through a "thermometer display" (Russo et al., 2021).

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